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FIFTY YEARS OF NAVAL ENGINEERING IN RETROSPECT.

PART I.

1888-1898.

BY HERBERT M. NEUHAUS, MEMBER.*

On September 30, 1888, a little group of officers of the Engineer Corps of the United States Navy met in one of the offices of the Bureau of Steam Engineering, and dedicated themselves to the formation of a society whose aim would be to advance the art of Naval Engineering, and particularly to provide for the proper presentation and preservation of trial trip data, and to provide a place of record for the debatable questions which were being met and settled as the first large Naval expansion following the Civil War slowly gained momentum.

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No minutes of that historic meeting are now extant. Through information developed subsequently from diaries, and from conversations in later life which have been had with officers who were present, we know that the name, "The American Society of Naval Engineers," was adopted at the suggestion of Mr. A. M. Mattice, then an officer of the Engineer Corps. The diary of Rear Admiral G. W. Baird, U. S. N., states that those present included: W. S. Moore, A. M. Mattice, W. H. Nauman, F. C. Bieg, G. Kaemmerling, W. H. Chambers, R. S. Griffin, and others. Some twenty-five years later, Rear Admiral John R. Edwards in an article discussing the organization of the Society considered that it was more than probable that the following names might be added to the list: C. H. DeValin, B. C. Bryan, W. H. Allen, Stacy Potts, H. P. Norton, W. D. Weaver, R. B. Higgins, Victor Blue and Ward Winchell. It is also known that Benjamin F. Isherwood, the then Engineer-in-Chief George W. Melville, Fred G. McKean, W. M. McFarland, and Emil Theiss did much to get the young organization under way.

It is interesting to note that in the organizing meeting each officer present solemnly contributed a quarter toward the treasury, and that Chief Engineer N. P. Towne was elected President and Passed Assistant Engineer R. S. Griffin was made the Secretary-Treasurer. A quarterly issue of a Journal was decided upon, and in due course the first number made its appearance in February, 1889. The JOURNAL *has been published regularly since that time, gaining slowly and regularly in its circulation and prestige until today it goes to over one thousand members, and in addition goes by subscription to some six hundred libraries, colleges, admiralties, and industrial concerns all over the world.*

From its earliest beginning up to the present time, the Society has adhered to one aim, "the advancement of Naval Engineering," and maintained its objective as a non-profit making scientific association. Over its fifty years of life its cost to sustaining members has always been five dollars a year, and that despite a doubling and trebling of the cost of production of its JOURNAL. *Over the years it has, in addition, built up a sufficient back-log of funds to tide production over periods of financial stress and retrogression. It is in a sound financial position today.*

No discussion of the Society's history could be considered complete without paying tribute to the firm of R. Beresford, the printers, who for half a century now have sent the JOURNAL *to press. In the early years, Mr. R. Beresford himself supervised the difficult and arduous job of reducing to type the highly technical articles continuously presented, and puzzled out a clear rendition of the involved and complicated formulae found in every issue. His daughter has succeeded him most ably, and has inherited the pride he felt in getting out the publication, a matter which has been of inestimable value to the many secretary-treasurers.*

To commemorate the lapse of this fifty years of engineering endeavor, marked as it has been with an almost inconceivable advance in efficiency and progress, it has seemed appropriate to include in the four numbers of the JOURNAL *to be published this year, a running resumé of that accomplishment, largely gleaned from old numbers of the* JOURNAL *itself. This monumental and very difficult task has been undertaken by the author, and it is hoped that it will prove to be timely and interesting. As will be noted from the subject, the present article will deal principally with the ten-year period which commenced with the organization of the Society, and which culminated with the Spanish-American War in 1898. The second article will cover the next ten years, culminating with the arrival of the first American turbine-driven battleship in 1908. The third article will deal with the period 1908 to 1921, thus carrying us to the Washington Treaty era, while the last article will bring us from that point briefly up to date.*

INTRODUCTION.

In order to visualize clearly the situation which confronted the American naval engineers of 1888, it is necessary to review briefly the modest but revolutionary marine engineering accomplishment of the previous half century. The pioneer steam war vessel of all navies was built in this country in 1814—the amazing *Demologos* —but the cessation of hostilities in the War of 1812 caused interest in the vessel to die out, and it never was brought into action. This unfortunate circumstance undoubtedly postoned the development of marine steam propulsion for some twenty-five years.

Thus, steam propulsion may properly be said to have entered our Navy with the completion and successful trials of the *Fulton 2nd* in 1837. Although the vessel easily made twelve knots, and later in a triumphant test outdistanced the *Great Western* to demonstrate the superiority of steam over sail, progress in the installation of steam propulsion plants was unbelievably slow when we now consider the gain achieved. Each steam-powered ship was bitterly opposed in the Navy itself, loath to give up its confidence and ultimate reliance on the efficacy of sail. The struggle was waged inconclusively over many years, until the War of the Rebellion intervened to largely settle the controversy, with the creation of the *Monitor* and the ironclads, upon which sails became definitely ridiculous. Yet even this demonstration did not settle the matter. We are so ruled by tradition, and most of us are so inherently bound by conservatism, that it is not surprising to see a sailing rig specified on fighting ships laid down twenty years after the Civil War.

However, the period from 1837 on was marked by a slow and cautious development in the design of the steam propulsion plants, always as auxiliary to sail. Side and paddle wheel engines commenced to give way to screw propeller installations when, in 1843, the U. S. S. *Princeton,* a brainchild of John Ericsson, and equipped with propellers, ran trials so successful that the interest of the whole country was stimulated. A few years later a surface condenser was developed and successfully employed, and in 1850 we witness the first crude attempt at a forced ventilation system.

In 1867 the Navy carried out its first experiments on the burning of fuel-oil, but with such a conspicuous lack of success that further development was retarded for nearly twenty-five more years; but in the same year it created the first fast cruiser, the *Wampanoag,* with a then unheard of speed of eighteen knots, after designs prepared by the brilliant Benjamin Isherwood.

The Bureau of Steam Engineering came into being during the Civil War, but for many years during and after the war its development and usefulness was retarded by the constant bickering which marked the personnel relations of the old line officers and the youthful engineer corps; by an intense lethargy which possessed the country after the War, preventing shipbuilding of any kind;

and when this had passed, by an amazing reversion to sail, dictated by motives of conservatism and economy.

Awakening from this static situation in 1883, Congress appropriated funds for the building of our first steel men-of-war, the well-known *Atlanta, Boston, Chicago,* and *Dolphin,* and although actual construction did not start on the vessels until 1886, their design was prosecuted with a new progressive thought, and great enthusiasm. Particularly noteworthy in these vessels was a specification requirement that all steel entering into the construction of the vessels should be of domestic manufacture, a constructive and potent clause, which, with the commencement of these vessels, set the birthdate of the country's "heavy industry", ultimately destined to make us the greatest steel-makers in the world.

In 1887, Admiral Melville of *Jeannette* and Arctic fame took over the reins of the Bureau of Steam Engineering as its Engineer-in-Chief. Of him it has been said, "After his accession to the office of Engineer-in-Chief, bidders for new vessels ceased supplying machinery designs of their own and gladly accepted those furnished by the Bureau of Steam Engineering." On such a happy note the American Society of Naval Engineers came into being, and Naval Engineering entered upon the career of revolution and progress which we find recorded in its JOURNALS over half a century of publication.

The Bureau of Steam Engineering at this early day was a comparatively small organization headed by the Engineer-in-Chief, George Melville. Its activities were confined chiefly to the design and maintenance of propulsive equipment in steam vessels, inspection service, and experimental tests on board vessels or at Navy yards. Although electricity had found a definite place in the Navy, cognizance over it had been placed with the Bureau of Equipment when the Bureaus of Steam Engineering, Navigation, Equipment, and Construction were created in 1862, and, as engineers aboard ship had to supply steam for, and maintain the generators and electrical supply, much dissension ensued because of the divided control. Complaints relative to the situation frequently reached the Secretary of the Navy, particularly in the Engineer-in-Chief's annual reports, but nothing was done to relieve the situation until the dissolution of the Bureau of Equipment twenty years later.

Engineering personnel had its troubles in these early days. The transition from sail to steam caused many of the "diehards" of the old Navy to fight viciously at the struggling young engineer corps which had been created as a separate entity from the line. Although pages of the JOURNAL rarely refer to the struggle for recognition taking place, considerable friction existed at times. Admiral Melville on one occasion made complaint to the Secretary of the Navy because of commanding officers using portions of the engineer's force, particularly coal heavers, for duties other than engineering.

Over many years, "coal-passing" had always been performed by the deckhands on board ship, and this disagreeable chore was thoroughly disliked by them. Therefore, in spite of the extra rations of grog which were issued after coaling ship, or hoisting out ashes, assignment to the "black gang" was considered a major form of punishment by the sailors. It is not surprising then to note an order issued by Admiral Melville to all commanding officers, forbidding the use of idle boilers in trimming ship. The dissension between sailors and engineers, between the line and the engineer corps, continued unabated until near the close of the century when Congress stepped in and drafted legislation which amalgamated the officers below decks with those above without distinction or caste.

Activities of the Bureau of Steam Engineering were not limited to personnel and petty feuds. With the new building program for increasing the Navy practically all designs for machinery were made within the Bureau. At the various Navy yards tests were made of fuel and lubricating oils, propellers, evaporators, and machinery. The Bureau was also called upon to make tests of pumping equipment for the District of Columbia. Much of this was done by Chief Engineer Baird, U. S. N., who was also the superintendent of the State, War, and Navy Building. That these Naval officers participated in other than purely Naval engineering is illustrated by the installation of an air-conditioning system in the White House during the illness of President Garfield. Here filtered air from blowers was passed over ice into the sickroom much as in some present day installations. Humidity was even then recognized as the principal and most disturbing factor in air conditioning.

Along with their normal functions, engineer officers also found time to deliver series of lectures before various audiences, thus adding greatly to the prestige of the small group. One series of four lectures by Past Assistant Engineer Hollis was delivered in 1892 before the Naval War College at Newport, Rhode Island, the lectures being on machinery, boilers, and personnel of our new ships. Engineers were frequently appointed to positions as professors in colleges and universities.

At the beginning of the year 1888, when the American Society of Naval Engineers was formed, the United States had under construction nineteen vessels, of which two were armored cruisers, one a coast defense vessel, five monitors, five protected cruisers, four gunboats, with the remaining two being more or less experimental types, one a torpedo boat, the other a dynamite cruiser. The first four vessels of a new Navy were already in commission, and triple expansion engines had replaced compound engines for propulsion purposes because of economy. Speeds of nineteen knots were being guaranteed by the builders of the *Philadelphia* and *San Francisco,* with a then high speed of twenty-three knots estimated for the torpedo boat *Ericsson.* Among the vessels building, the *Maine* and *Texas,* the *Ericsson* and the dynamite cruiser *Vesuvius* had vertical engines, a radical change instituted by Admiral Melville.

The *Vesuvius* was the first vessel equipped with a vertical triple expansion engine installation to be placed in operation in our Navy. Interest centered in her, not only because of the ordnance installation which comprised compressed air guns for throwing dynamite bombs, but because of the high speed of twenty knots specified in the contract. Her first preliminary trials were held in October, 1888. As appears usual on such trials, slight defects were uncovered, and official trials were not held until December of the same year. Steam pressure was 162 pounds at the start, and 144 at the finish, at 264 revolutions per minute. It is interesting to note here that as steam expansions increased, steam pressures also increased. On the first run with the tide, a speed of 21.47 knots over the ground was made with her twin screws, but on the return a bed plate under a blower engine broke which reduced the speed to bring the average below 20 knots. Her third set of official trials averaged 21.646 knots which was considerably over the contract requirement.

Trials of the *Charleston* and *Baltimore* followed the same year, a notable feature in these vessels being their designs which were made in England. No further foreign engine plans were made after this for United States Naval machinery, all subsequent vessels being designed in this country, except for those later purchased complete abroad. The *Rochester* was also notable in that she was the first major war vessel in this country to be constructed without sails, military masts replacing the traditional square rig and marking the final triumph of steam over sail.

New ships were being authorized each year, with the Secretary of the Navy emphasizing during these early years our lack of battleships and torpedo boats. The situation was somewhat acute, for in the twenty years following the Civil War, very few vessels had been built in this country, and those vessels which continued in use had little fighting value, wooden hulls, and were badly in need of repairs. To accelerate the demand, European nations had engaged in a shipbuilding race, and in 1890 England alone had two hundred and seven torpedo boats with France close behind with one hundred and ninety-one. The United States answered with one, the *Ericsson,* whose trials were held in March of that year. She was an unusual craft with a 105-ton displacement, 137.5 feet long, and 15-foot beam, the hull having a ram bow and an overhanging stern. Twin screws, each directly driven by a five-cylinder, quadruple expansion engine of the vertical overhead type, were fitted. Frames of turned steel rods braced diagonally, also formed the cap bolts of the main bearings. Valves were of the piston type worked from cranks on a small shaft, parallel to the main shaft and driven from it by gears. (Figure 1 shows a similar engine of the *Cushing.*) No pumps operated from the engine, all being independent. One condenser served for both engines and all auxiliaries, injection being secured underway by a scoop, with a centrifugal steam driven pump for use when not in motion. Two boilers of Thornycroft design, but built in America, were furnished by the Herreshoff Manufacturing Company, builders of the *Ericsson.* Coal was used as fuel, steam being raised from cold water in half an hour, with four inches of air pressure being supplied to a closed fireroom. A steam pressure of 250 pounds or less at the boilers was regulated by the blower engine throttles in the engine room. On a three-hour

FIGURE 1.—STARBOARD ENGINE OF U. S. TORPEDO BOAT "CUSHING."

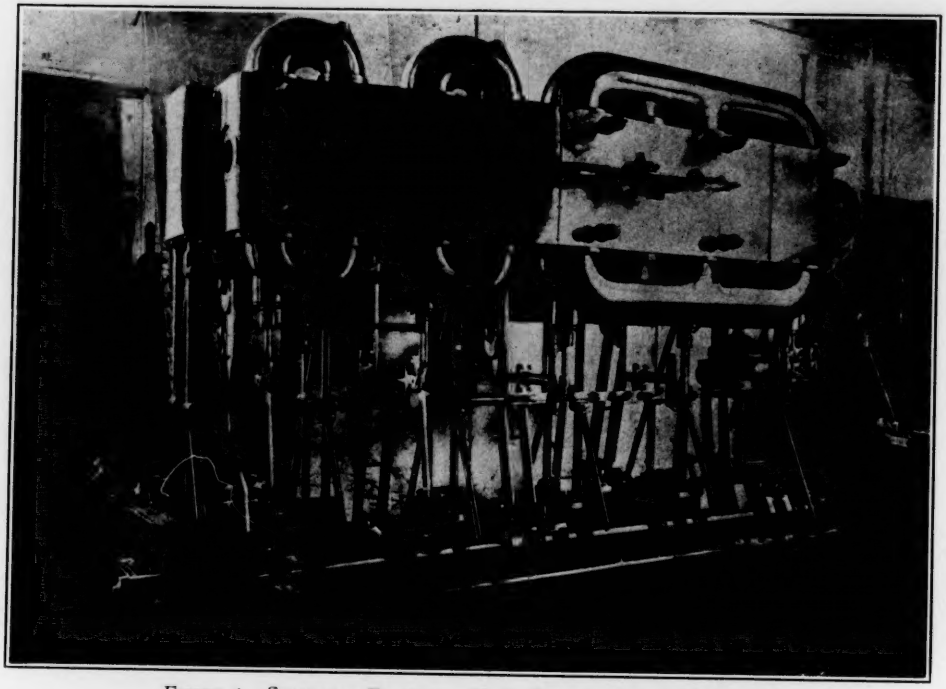


FIGURE 1.—STARBOARD ENGINE OF U. S. TORPEDO BOAT "CUSHING."

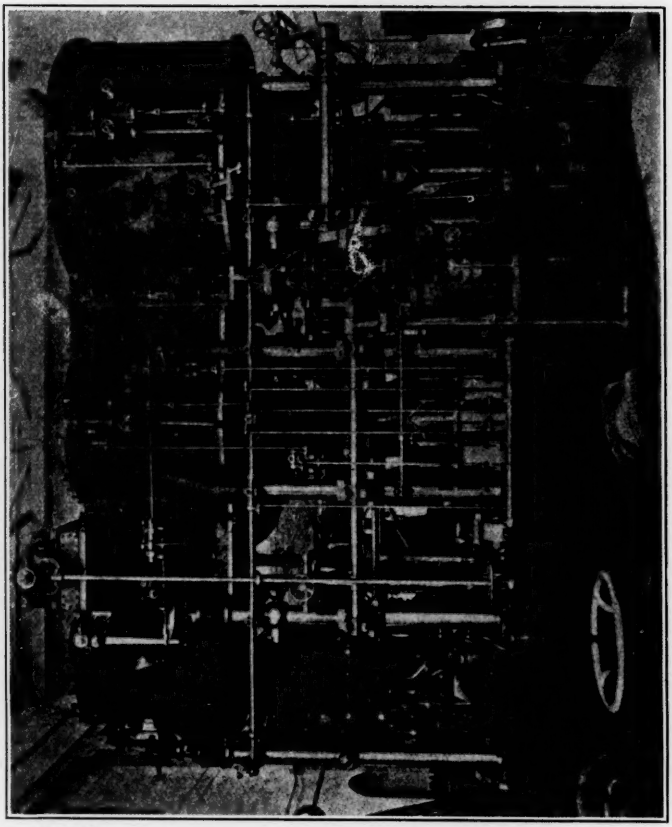


FIGURE 4.—ENGINES OF THE "MAINE."

run at 22.5 knots, 2 pounds of coal were burned per indicated horsepower per hour.

Congress in a new appropriation bill (1891), now provided for three new battleships of 9000 tons displacement and 15 knots speed. They were to be twin screw ships with triple expansion vertical engines making about 128 revolutions per minute and delivering 9000 indicated horsepower. Four double-ended Scotch boilers having 32 furnaces, and two auxiliary boilers with four furnaces each, furnished steam for the installation. The firm of Cramp and Sons bid $2,990,000 for the construction of one battleship. In the appropriation were also included funds for the construction of protected cruiser No. 12, later named *Columbia*. Here again appears an innovation of Melville. The high speed of 23 knots demanded, with the corresponding large horsepower required, together with a lack of overhead space, forced a decision to use three screws, the first such arrangement in our Navy. (Figures 2 and 3.) Multiple screws were not new to our service, several four propeller barges having been used in the opening of the Mississippi River during the Civil War, but these were small vessels and the service was not comparative. Melville held that triple screws enabled smaller separate sets of machinery, higher rotative speeds to be employed with safety, and greater economy at ordinary cruising speeds with only one engine working. The decision was partially based on Isherwood's original propeller experiments at Mare Island, which formed the basis of propeller design in the Navy for almost thirty years.

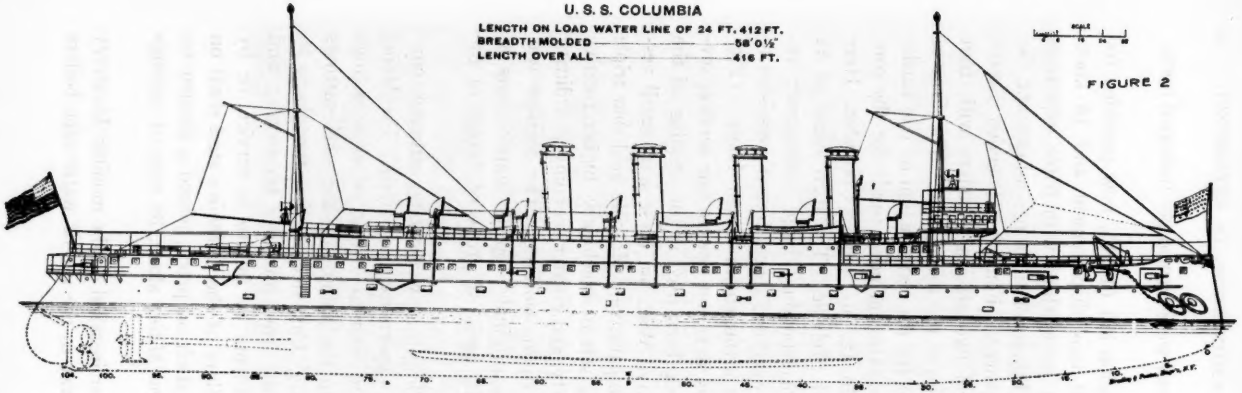
Progress of all vessels building was well along, although considerable changes were made as experience was gained. The *Maine* was finished with forged engine columns instead of with castings as had been customary, due to the failure of the steel castings originally provided. (Figure 4.) Cast steel, at first thought to be a panacea for all the ills of cast iron, proved a boomerang, and created several unpleasant incidents by failure in service, or by wholesale costly rejection. Failure of the *Dolphin's* steel shaft on trials, and the *Boston's* thrust shaft on proof, placed a damper on the use of steel shafts. On the *Maine* alone, 36 tons of castings were rejected.

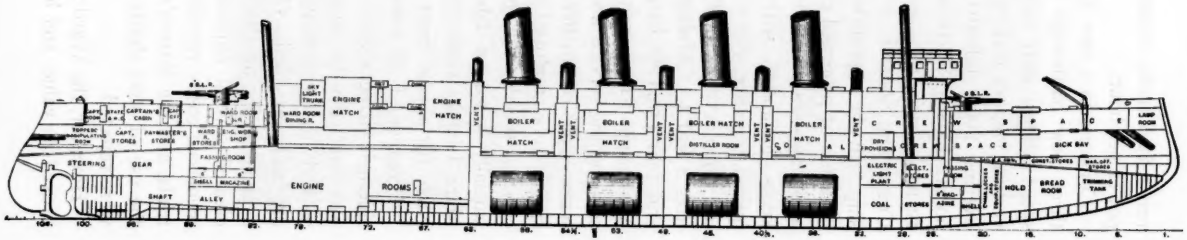
However, the Ward coil boiler installed on the monitor *Monterey* proved its value, and led the way to the use of water tube boilers

U. S. S. COLUMBIA

LENGTH ON LOAD WATER LINE OF 24 FT. 412 FT.
BREADTH MOLDED ——— 58' 0½"
LENGTH OVER ALL ——— 416 FT.

FIGURE 2





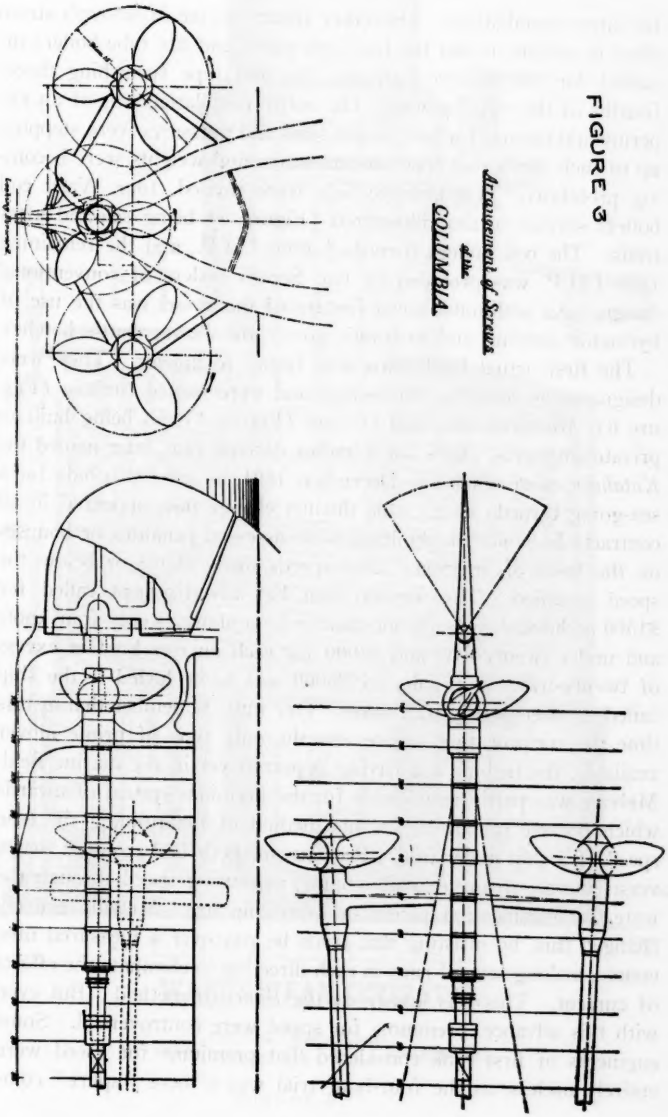
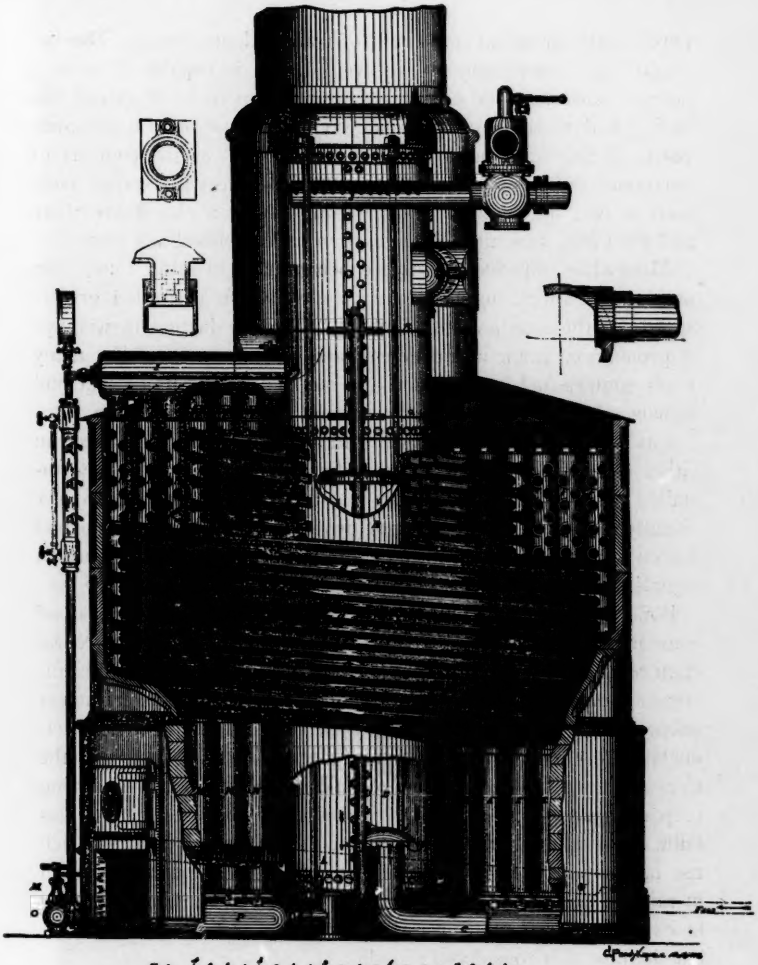


FIGURE 3

Arrangement of Screws of the COLUMBIA.

for larger installations. One other feature of the *Monterey's* steam plant is notable in that she had both water and fire tube boilers installed for comparative purposes, the first type furnishing three-fourths of the ship's power. The entire installation was of an experimental nature, for both boiler sizes and pressures were stepping up to such limits that space requirements and weights were becoming prohibitive. Competitive bids were invited, four Ward coil boilers similar to that illustrated (Figure 5) being selected after trials. The coil boilers furnished 4200 I.H.P., and the remaining 1200 I.H.P. was provided by two Scotch boilers of conventional design. An additional novel feature of the vessel was the use of hydraulic steering and hydraulic power for closing battle hatches.

The first actual battleships now began to appear. They were designated as coast-line battleships and were named *Indiana* (Figure 6), *Massachusetts,* and *Oregon* (Figure 7), all being built in private shipyards. Bids for a harbor defense ram, later named the *Katahdin,* were opened in December, 1891, as were also bids for a sea-going torpedo boat. One distinct change now appeared in all contracts by which shipbuilders were assessed penalties or bonuses on the basis of fractional knot speeds made above or below the speed specified. The torpedo boat bid advertisement called for $1500 additional for each one-quarter knot above twenty-four knots and under twenty-five, and $2000 for each quarter knot in excess of twenty-five. A penalty of $5000 was to be levied if the ship failed to meet twenty-four knots. One must remember that at this time the reciprocating engine was the only type of prime mover available, the turbine not having appeared yet in the marine field. Melville was partly responsible for the premium system of awards which became practicable by his method of determining the true speed of a ship under trial. Previous methods had required that a vessel merely steam a steady course, measuring speed through the water by means of a patent or even chip log. Melville entirely changed this, by insisting that trials be run over a measured mile course, making several runs in each direction to eliminate the effects of current. This was known as the *Bancroft* method. But even with this advance, premiums for speed were controversial. Some engineers of first rank considered that premiums for speed were entirely useless, as the four-hour trial was a mere "spurt" com-



WARD'S STEAM GENERATOR.

TOTAL { HEATING SURFACE 1981 / GRATE " 48 } SQUARE FEET

FIGURE 5

pared to the sustained speed runs of trans-Atlantic liners. They insisted that "machinery of a given design is capable of only a definite power and no amount of reward can make it exceed this limit," and recommended accordingly, premiums on a horsepower basis. Trials brought up other questions such as the comfort of personnel. The closed fire room and closed ash pit system were both in use, the *Newark* and *Concord* having a closed fire room and the *Charleston* and *San Francisco* having closed ash pits.

Meanwhile improvements were being made in other lines. An oscillating blower engine was developed which permitted greater speeds of the fans and consequently a large reduction in weights. A pronounced single improvement came in ship control. For many years engines had been started and stopped by means of bell pull signals. Where before one bell meant "ahead slow," two bells, "stop," and three bells, "back," with a jingle bell for full speed in either direction, a mechanical and electrical telegraph was now installed between the engine room and bridge, registering the order visually, with an acknowledging return signal. Early telegraphs had a deep sounding gong for ahead signals and a shrill gong for astern signals, though these were soon after merged into one gong.

Boilers came in for their share of change. Lap welded tubes had come into use in 1890, and in 1891 in the presence of several Naval engineers, tests were run on a Serve's ribbed boiler tube for increasing evaporative surface. These latter, however, were never adopted for Naval use. Even with the constant improvement accidents were not uncommon, as the records testify. On board the *Concord,* a serious explosion of a main steam pipe occurred during preparations for final trials. This particular main steam pipe was built up of copper sheet with a brazed seam. Steel pipe for such use had not become common, the spiral welded pipe having been mentioned only two years before. The Board of Inquiry submitted in its findings that the cause of the casualty was a water hammer, but the pipe was considered sound.

New ships were constantly added to the building program, though none of this work was assigned to Navy yards. Each new design of vessel brought in some changes. The *Columbia,* for example, introduced the Stevenson link motion for valve control of the main engines, which marked the subsequent gradual elimination of the

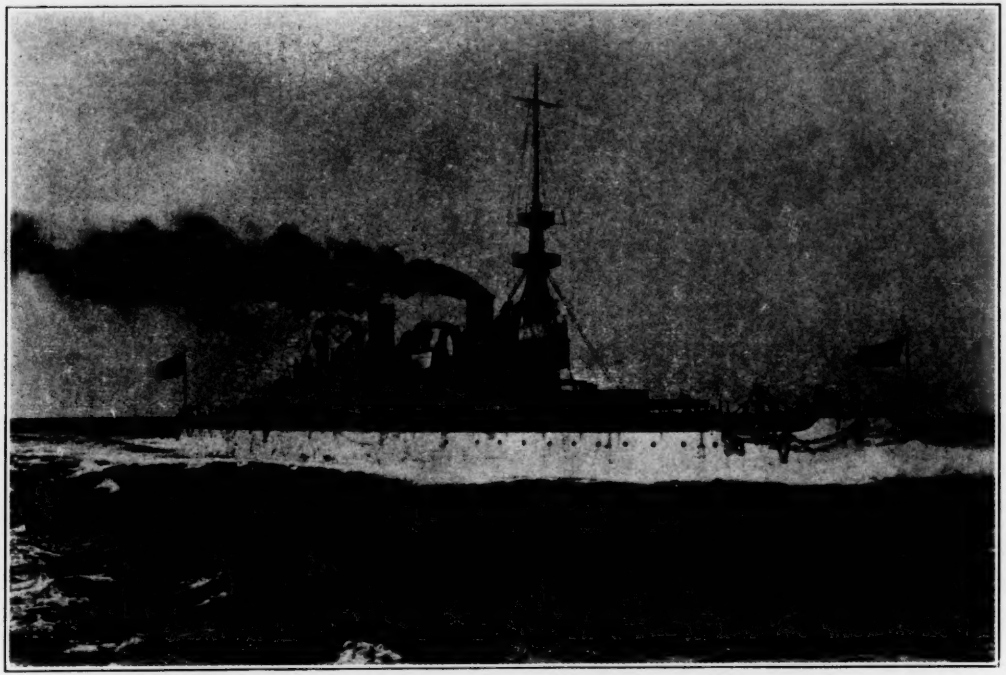


FIGURE 6.—U. S. S. "INDIANA."

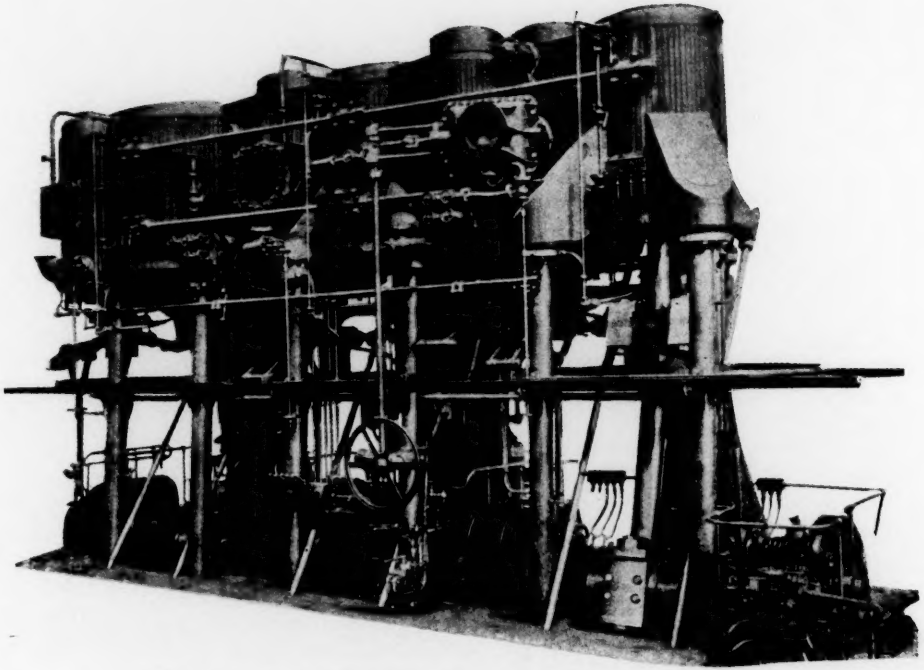


FIGURE 7.—TRIPLE-EXPANSION ENGINE OF THE U. S. S. "OREGON."

Marshall valve gear that had been standard for several years. Also, the advent of triple-expansion engines brought in higher steam pressures, the high-pressure boiler, and feed heating, and a distinct new type of feed water heater was developed. Design features of these heaters were not much different from those of today, one type having spiral corrugated tubes for increasing the rate of heat transfer. Large Scotch boilers were using hydrokineters, or hydraulic jets, to maintain circulation of the water in the boiler and to prevent cold spots.

Some features of operation and the study given to them may be mentioned here. Lubrication of the engines was performed by regularly appointed oilers who saw that all oil cups and reservoirs were kept properly filled. Some of the older reservoirs were filled with matted horsehair to provide for a proper flow of oil to the bearings. The year 1879 marked a distinct departure from previous practice when mineral oils were specified as lubricants, though both organic and mineral oils were used jointly for several years thereafter. Boilers, too, offered a distinct problem and much study ashore and afloat was given them. Scale formation caused much trouble, a case in point being the *Charleston's* chase of the *Itata* to South America in 1891, during the Chilean civil war, when the *Itata,* which was carrying contraband, was forced to stop for fifty hours to clean a boiler and repair a bulged crown sheet burned by reason of a heavy scale formation. As a result of the stoppage, the *Charleston* missed the *Itata.* One definite reason for the heavy formations of sulphate and carbonate in the boilers lay in the use of sea water for make-up feed purposes, for evaporators had not then come into common use and appeared only on an occasional merchant vessel. Boiler water treatment by caustic soda was attempted, but the results were not conclusive. Cylinder oil in the condensate was recognized as a prolific cause of failure. The greatest cause of "boiler decay" was corrosion, and in the early '90's electrolysis was recognized as a definite factor. It was found, too, that oxygen and carbon dioxide when entrained or dissolved in boiler water accelerated corrosion. Such deterioration meant replacement of the boiler tubes every three years, while the shells and furnaces showed but slight thinning. The increase in the size of engines, and also the multiplying auxiliaries to be attended, did not

decrease the engineer's task. By 1892, the Allen dense air refrigerating machine, to mention one auxiliary, was making its appearance in one-ton size on some of our vessels.

Naval building increased steadily through the '90's, and new ideas were constantly being tried. In the *New York* and *Brooklyn,* armored cruisers, two engines were installed on each shaft, the forward engines capable of being disconnected from the after for cruising purposes. Each engine also had one section of nickel steel line shafting and each had its own condenser. Turrets were driven by steam engines with handwheel controls at the various sighting stations. Metallic dial thermometers appeared for the first time to replace those of the customary mercurial type, and evaporators with distillers having a combined capacity of 10,000 gallons per day were installed. The picture enlarged to include the first sea-going battleship in place of the coast line battleships previously built and building.

One notable change appeared in 1892. Admiral Melville was responsible, and in a memorandum dated October, 1892, to the Secretary of the Navy, he outlined the advantages of 100-foot smoke pipes for Armored Cruiser No. 3 (later the *Brooklyn*) as follows:

". . . if a small additional increase (speed) is wanted, say 1 knot, this can be obtained with a moderate increased air pressure from the blowers. With the short pipe, ½ inch pressure would be required, besides the amount needed with the high pipe.

It is thus seen that the high pipe . . .

Increases the speed without injury to anything.

Increases the life of the boiler.

Increases the economy of combustion at moderate powers.

Saves coal lost by radiation from extra boilers used with short pipes.

Saves in repairs to boilers.

Saves in repairs to blowers.

Saves extra coal needed to run blowers.

It should, perhaps, have been distinctly stated at the start that this height of 100 feet is above the lowest grates of the boiler furnaces."

Done in the characteristic positive Melville manner, the explanation is here found for the type of smoke pipe peculiar to our Navy

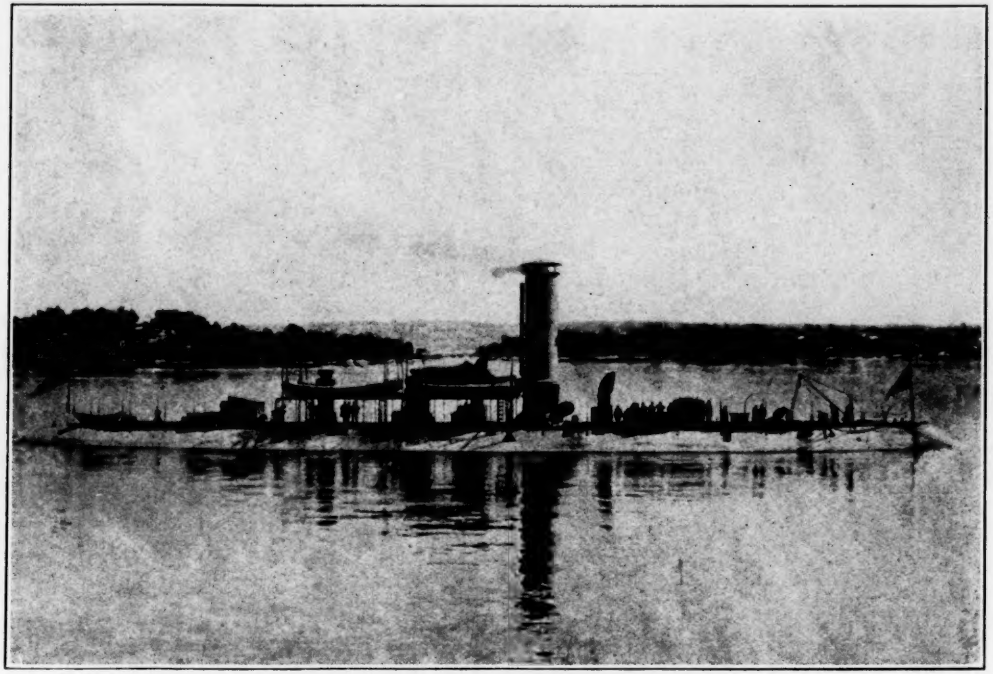


FIGURE 8.—U. S. S. "KATAHDIN."

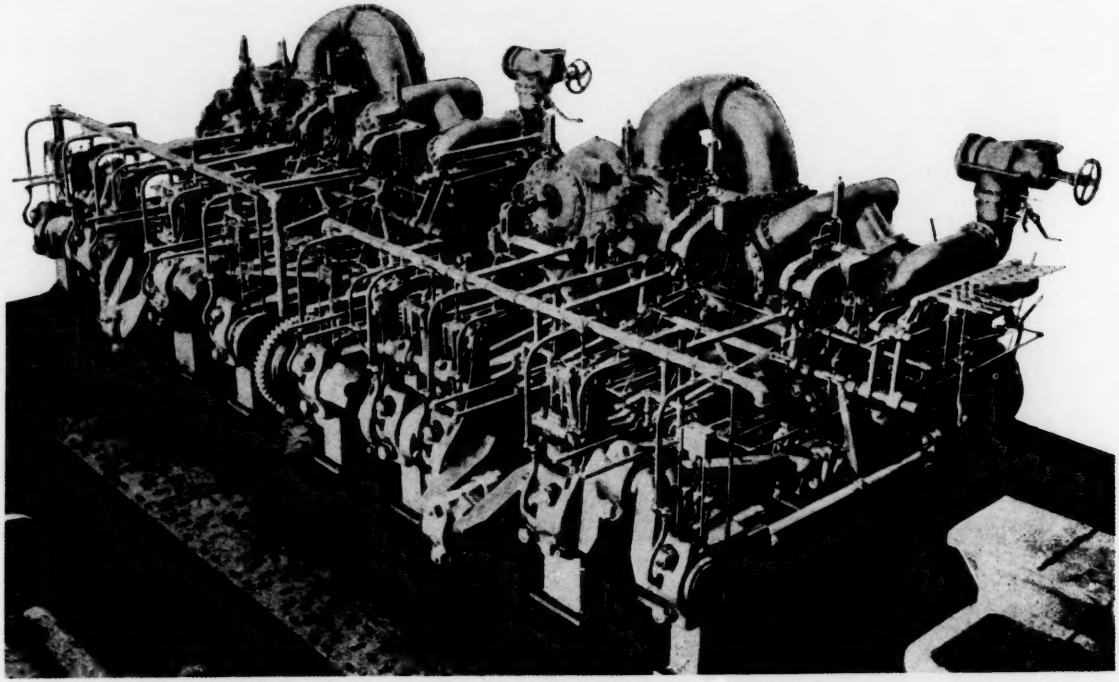


FIGURE 9.—STARBOARD ENGINE, U. S. S. "KATAHDIN."

for several years. One has but to look at the old designs and models to note the conspicuous silhouette given by the high smoke pipe which was carried well into the next century.

The year 1893 saw the launching of the ram *Katahdin.* (Figure 8.) She was designed for harbor defense work only, and was probably one of the last of our vessels to be designed with horizontal engines. (Figure 9.) Trends of design were now away from harbor defense vessels such as monitors or rams, and were toward large ships with pronounced sea-keeping qualities. This is evidenced by the start of the Navy's three sea-going battleships previously mentioned. In the same year, 1893, the Naval Academy Practice vessel *Bancroft* had her trials. She is notable because her speed was determined by standardizing her screws in a series of progressive trials over a measured mile to determine accurately the relationship of speed and revolutions. Use of the new method eliminated 40-mile trial courses, with vessels stationed at intervals to make current observations, and pilot vessels to precede the ship on trial to see that observers were at their stations and that the course was clear. So many advantages attached to the method that it has continued in use to this day. A novel feature of the *Bancroft's* construction is found in her special machinery designed after high-speed stationary engines built by the contractor, in which all working parts were made absolutely true, the piston, valve rods, and shafting being "ground true." Trials of the *Columbia,* first of the United States triple screw cruisers were held late in 1893. Her size made her the largest man-of-war ever to have this installation except for the German *Kaiserin Augusta,* which held her trials shortly before. Arrangement of the screws is shown on the two sketches (Figures 2 and 3), two screws located outboard of the single amidships screw. Another distinction held by the *Columbia* is found in her length of 411 feet, which made her at that time the longest vessel in the Navy. Her appearance was somewhat similar to a merchant vessel, the intention being to equip her for commerce raiding. Provision was made to disconnect the idle engines by removing coupling bolts just forward of the thrust bearings and allowing the unused propellers to idle. Brakes were attached to each shaft to permit coupling when the ship was underway. Ninety-six separate engines were installed for various purposes, the num-

ber being larger than any other vessel, including the *New York,* which until then had held the record. More electrical interior communication instruments were installed than in any ship previously, which indicated the growing dependence upon ship control systems. On her contract trials a mean speed of 22.92 knots was developed with a maximum of 25.30 knots for one run which was a phenomenal speed in those years.

In a lecture before the Naval War College in 1894 by Past Assistant Engineer W. M. McFarland, he gave as the principal reason for the adoption of the increase of steam pressure and range of expansion, that economy was almost solely the answer, while a definite reduction in the huge Scotch boiler weights followed the use of the higher pressures. Most foreign nations had adopted the triple expansion engines, and some had used quadruple expansion in a few cases. Each increase in pressure was the result of further advances in steel manufacture, with a commercial production of thicker plates and more uniform quality. Originally a factor of safety of 8 was used in calculating boiler shell strength, but by this time the factor had dropped to from 4 to 4½. Condensers were made of composition instead of cast iron which also gave reduced weight. The question of weight was still acute in boiler design, as Scotch boilers for the Navy were still in use with a 16-foot diameter, double ended, with four furnaces at each end. However, tubulous boilers were now coming in, and although they possessed the triple disadvantage of being more susceptible to corrosion, greater difficulty in feeding, and the inability to plug a leaky tube without withdrawing the boiler from service, the advantages of safety, rapid steaming, and great reduction in weight far outweighed the disadvantages.

Steam piping also came in for change. Originally, steam piping was made of brazed copper sheet, in some cases banded by metal rings at regular intervals. After several serious casualties in our Navy and abroad as steam pressures increased, search was made for a more reliable substitute. Welded steel steam pipe had appeared, and were used in the *Columbia* and *Minneapolis.* Some of these pipes were 20 inches inside diameter, three-eighths of an inch thick and sixteen feet long. Specifications called for a water test pressure of 400 pounds per square inch. Severe tests were given

an experimental section of this lap-welded pipe, the pressure being carried without leakage to as high as 1000 pounds, pinhole leaks developing at 1500 pounds and explosion occurring at 1700 pounds. To all concerned, the test was very satisfactory, the bursting occurring away from the welded flanges and seam.

One other test may be of interest for it illustrates the wide field which had to be covered by engineers of that day. Of course, fuel tests were run frequently on all types of coal, and oil tests were started on the *Palos* in 1867 to determine the value of petroleum fuels. However, in this test is the first record of experiments using coke as fuel to determine its "potential and economic efficiency." The dispatch vessel, *Dolphin,* was used in the trials on a trip from Washington to New York, a period of 27½ hours. By burning coke previously weighed and averaged, a careful record was kept of its consumption. Readings were also taken on all auxiliaries and their steam consumption. The net result of this experiment was a demonstration that coke occupied too much space for the value received, and more coal passers were required to handle the greater bulk. So the use of coal continued.

When the new Navy came into being, with its multitude of ships of high power, many questions arose as to the contract provisions for bonuses and penalties to be awarded for meeting speed requirements. A cause of controversy was the failure of the *Dolphin* to meet her horsepower requirements. When Secretary Whitney came into office, he decided that the contracts had been too loosely drawn, and called on a number of contractors to see whether they were willing to submit proposals under a contract form which he had devised. In the first draft there was no provision for adjusted settlement for, as the contract was worded, the slightest falling off in speed meant rejection of the ship. No contractor was willing to undertake such a risk, and Mr. Cramp of the Cramp Shipbuilding Company proposed graded penalties to be assessed for each degree of non-compliance down to a certain minimum, when absolute rejection would ensue. Reciprocally, bonuses or premiums were offered for performances in excess of the contract requirements. The proposal appeared so reasonable that it formed a part of every Navy Department contract for the new vessels from this time forward. The first few ships had these penalty and bonus provisions

written around horsepower, while the later vessels were covered by speed requirements. In one case, bids were requested for an 18-knot vessel but none were received within the appropriation limitation. However, when she was readvertised as a 17-knot vessel with speed bonuses, and contract was awarded, she did so well that the final cost to the Government was the same as if the original bids had been accepted.

The Bureau of Steam Engineering was exploring in many new fields. Oil as fuel has been mentioned before. Now serious consideration was given to its use in torpedo boat boilers, principally because of the ease with which steam could be raised. Further studies were being made of oil burning installation for these vessels, and much thought was given to a safe development.

Consideration was now given to the desirability of repair ships. The idea was not new, because during the Civil War floating anchored hulks had been so used. However, those under study were intended to perform regular cruising duty and serve with the fleet, the repair personnel being skilled specialists who would perform only repair work, while such personnel aboard fighting ships also stood watches. A vessel of this type was actually started during the Chilean excitement of 1892, when this Government took over the Inman Line steamer *Ohio* and began transforming her for this duty. Her shops were to include a foundry with a cupola, a large machine shop, a coppersmith shop, a blacksmith shop, and a boiler shop. When the tension subsided, however, the conversion was abandoned.

Almost every year brought new ships, and with them new designs. As the tonnage of vessels increased, so did speeds and powers. In 1896, Congress provided for construction by contract of three seagoing coast-line battleships of 11,000 tons each, with the highest practicable speed for their class. These were subsequently called the *Illinois, Alabama,* and *Wisconsin.* Three 30-knot torpedo boats were also included in this program, together with ten smaller torpedo boats. During the same year the trials of the *Brooklyn* were held. She was an armored cruiser of 9270 tons displacement and 20 knots speed. A description of her machinery plant which follows is typical of the majority of large United States war vessels then building. Her main engines were of the vertical, direct acting,

triple expansion type common at the time. Four engines, two on each shaft, but in separate compartments, made up the main propulsion unit. As on the *New York,* the forward engines could be uncoupled for cruising purposes, the couplings being of the disc type with four tapered bolts. Intermediate and low pressure cylinders were steam jacketed, valves for each cylinder being of the piston type and having balancing pistons. The valve gear was of the Stephenson double-link type which varied the cut-off from 0.5 to 0.7 of the stroke. Reversing was accomplished by a reversing engine secured to the engine frame. The main pistons were of cast steel of the usual dished or conical type, with two packing rings. This vessel being of somewhat older design, the main steam pipes were of copper, reinforced with one-eighth inch steel bands, at intervals of six inches.

In the cranks, forged steel was used, while in the after line shaft sections, nickel steel was used, a horse-shoe pattern thrust bearing with white metal facings being used to take the thrust. Only bottom brasses were used in the shaft bearing, the cast steel caps and brasses being lined with white metal. Water circulation was provided for these, the crosshead guides, and thrust bearing in order to keep the surfaces cool. Main condensers were made in sections with cast brass shells, this type of construction having replaced the cast iron shell of previous years. Steam was directed by brass baffle plates over the outside of the tubes while water circulated through the tubes. Blake air pumps with their beam construction delivered the condensate to a main feed tank.

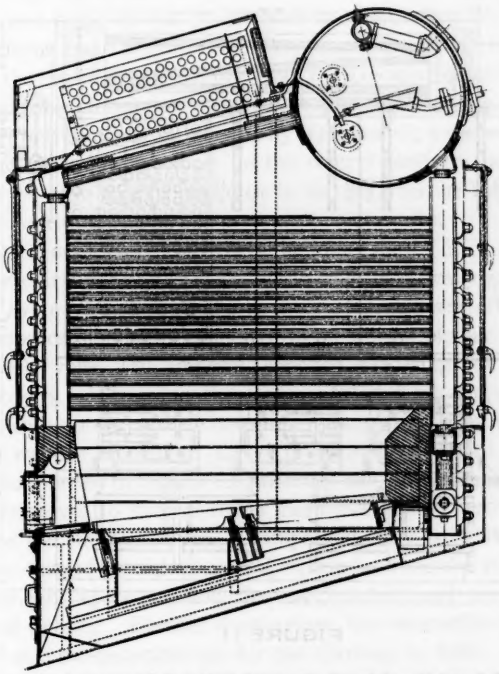
In the boiler room were found the typical cylindrical steel fire-tube boilers, these being sixteen feet, three inches in diameter, with a working pressure of 160 pounds per square inch. Five boilers were double-ended and two single-ended, each end having four furnaces of corrugated tube. The protected deck covered the boiler rooms and each fire room led to a single smoke pipe. In the boilers were tubes of lap welded and drawn charcoal iron, swelled at the forward ends, expanded and beaded over in the back. Shaking grates in each furnace had been so arranged that they could be easily renewed without hauling fires. A steam circulating apparatus furnished forced circulation to accelerate building up the steam pressure. Each compartment acted as a closed fire room, air being fur-

nished by two Sturtevant blowers to compartments which also contained the main and auxiliary feed pumps. In the gunboat *Nashville,* whose trials were run a year later, Yarrow water tube boilers were installed, indicating that this type of boiler was finding more universal use.

Other auxiliaries included traps, fire and bilge and water service pumps, turning engines, windlass engines, ash-hoisting engines, engine room steam driven blowers, turret turning engines, an Allen dense air ice machine, workshop engine, distilling and evaporating apparatus, and three 80-volt, 32-kilowatt direct-current generators. These latter furnished power to operate the searchlights, and 750 incandescent lamps. A separate generating set, new to the service, furnished power for operating the two forward turrets, though the *Iowa,* our first sea-going battleship, and completed about the same time, had her 12-inch turrets operated by hydraulic water motors.

Experimentation was very much in evidence as new vessels were laid down, the experiments generally beginning with the smallest vessels and progressively advancing to the larger. This is noteworthy in the *Wheeling* and *Marietta,* composite twin screw gunboats. Instead of open framing for the main engines, cast steel bed plates, and a single condenser for the two engines; composition bed plates were used to which were cast the back engine columns, and a condenser for each engine was provided. A Howden forced draft system substituted for the ordinary ash pit, and the grate bars were shortened. The *Marietta* had Babcock and Wilcox marine type water tube boilers, with ash pit draft, instead of conventional cylindrical boilers. Included in the boiler casings, but as entirely separate structures, were economizers or feed water heaters. As may be seen from the illustration (Figures 10 and 11), the installation consisted of the original Babcock and Wilcox boiler with the back water drums and sinusoidal tubes. The completion of the torpedo boat *Foote* also brought the Mosher water tube boiler into the Naval service, and the *Nashville,* which now had her trials, was equipped with Yarrow boilers. Coal, however, still remained the principal fuel with efficiencies varying widely, for the *Marietta* used nearly half a pound of coal more than the *Wheeling* and had an uptake temperature of 850 to 1100 degrees, compared with the other's 550 degrees Fahrenheit.

The crowning achievement of the American Naval designers came in the year 1898, when on March sixth the *Oregon* left the Naval Station at Puget Sound, being under way until May twenty-fourth, the date she anchored off Jupiter Inlet, Florida. Even to-day the trip is outstanding, for during the entire voyage of 14,500 miles she made but a total of eight stops, coaling at five, and with



BAFFLE PLATES ON TOP ROW AND ON SECOND ROW FROM BOTTOM.

FIGURE 10

but little time out for repairs, participated in the battle of Santiago, outstripping in the chase all United States vessels except the *Brooklyn*. Too much credit cannot be given the machinery design and construction, and still more credit must be given to the engineering personnel through whose perseverance everything was maintained in fighting trim.

The advances in fighting ship construction were not independent of industrial and scientific achievement. Rather, the ship construction reflected and adapted those advances to its own purposes though in many instances the Naval need was foster parent to the development. Such was the story of electricity. Historically, its first Naval appearance in the United States occurred in 1842, when

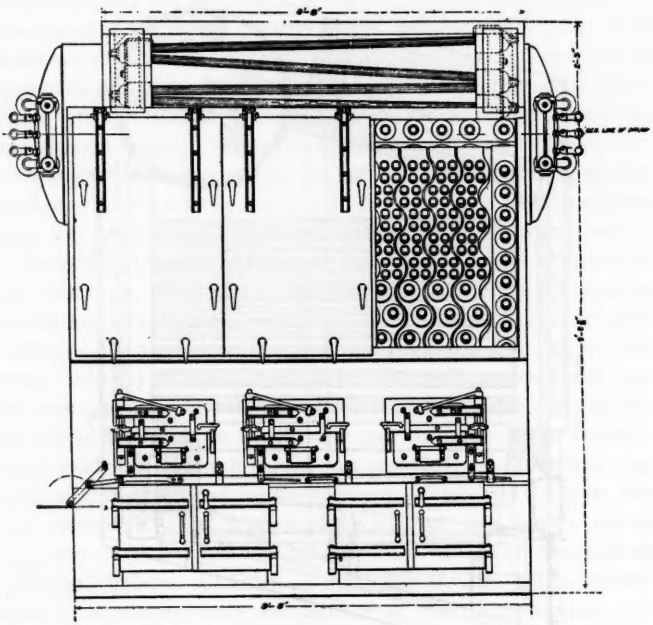


FIGURE 11

Samuel Colt of revolver fame, and Samuel Morse, the inventor of the telegraph, while on the old *North Carolina,* blew up a hulk anchored off the Battery in New York with an electrical firing circuit. Further use of electricity was made during the Civil War, principally by the Confederates in exploding submarine mines. In 1876, the torpedo boat *Lightning* was equipped with a Gramme generator of 500 candles, and a Farmer non-automatic arc lamp for use as a searchlight. Six years later followed the International Congress

when the electrical units were universally standardized. Previously, each country had had its own names for these units, the present ampere being known as the weber in this country and the present coulomb as the farad. Experimentation progressed rapidly and in 1877 the *Trenton* was equipped with an electrical call bell, gun control, and torpedo firing system. The telephone seems also to have been tried by the Bureau of Ordnance. A definite telephone installation was made on the *Philadelphia* in 1890, when the American Telephone and Telegraph Company provided a circuit from the bridge to the engine room, and one from the executive officer's office to the general storeroom. Intercommunication between engine rooms and firerooms was attempted by interphones; an unmitigated blessing to the engineer officer on the control platform, who was now relieved of a blast of coal dust in his ear when he had to call a fireroom operating under air pressure by voice-tube.

With the renaissance of our Naval building, the *U. S. S. Trenton* is found the first war vessel in the world to be electrically equipped, although by present day standards the system appears crude. A belted reciprocating engine connected to an Edison bipolar dynamo rated at 100 volts, 120 amperes, supplied 238 lamps of various candle powers. Wiring to the lamps consisted of copper wire, wrapped with cotton soaked in paint or tar, which was then enclosed in wooden moulding. Other installations followed rapidly, though the Bureau of Steam Engineering had no responsibility in the matter except to furnish steam and make repairs. A real advance was the standardization of lamps and bases in 1891. Voltages were carried at eighty, a compromise between the fifty volts for searchlight operation, and the one hundred and ten for incandescent lighting. Further development was insured by the provision of a turbo-generator set for the *Cushing* in 1894. Gunfire by electricity was introduced in 1896, and in the *Kearsarge*, a full electrical turret control was provided. All current was direct, and in the *Kearsarge* appeared our first three-wire system, which operated at 160 volts.

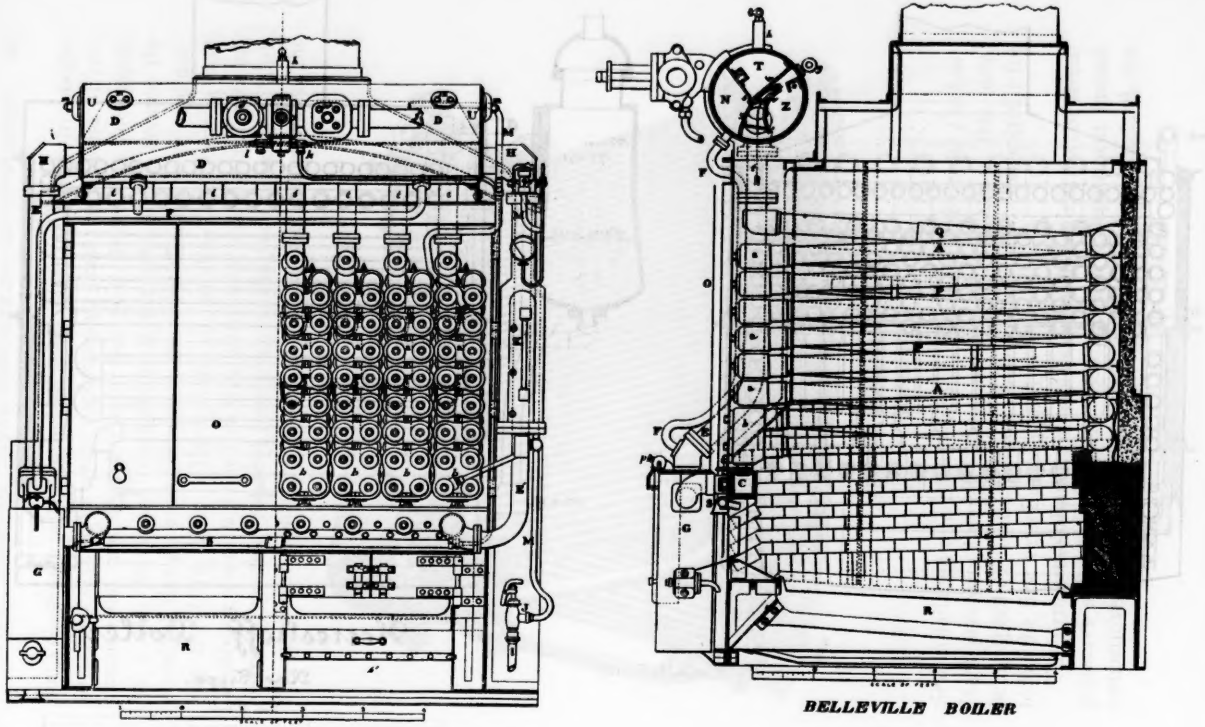
Fuel oil has frequently been mentioned in the preceding paragraphs yet nothing definite materialized from the study of its possible use. Foreign nations were attempting its adoption in their own vessels, and corporations like the Standard Oil Company had

expended large sums in experiment and investigation. The seriousness of the fuel question was shown by a Japanese purchase of Welsh coal of medium quality, to gain a half knot speed for their war vessels, the coal costing six times as much as coal from their own mines. The use of oil in America and foreign nations was not new. The Bureau of Steam Engineering had run tests of unrefined petroleum and its residuum before, Congress having provided $5000 for such tests in 1866. Similar tests had been made at the Navy Yard, New York. The Columbian Exposition at Chicago in 1893 was supplied with power from oil-fired boilers, as was the California Mid-Winter Fair. Russia had had indifferent success in burning oil and at this time led European nations in its use.

Considerable returns attached to the use of petroleum residue as fuel, among these being the saving of labor, more perfect combustion of liquid fuel, which prevented the formation of residuals and smoke, an enormous saving in space, and a much extended cruising radius. A very pointed demonstration of the first advantage was made by an ocean tramp, the *Baku Standard*, in a voyage from Shields to Philadelphia. This was probably the first ocean voyage made by an oil-burning vessel. Instead of the usual crew of firemen and trimmers, only three water tenders were shipped. One was unfortunate enough to be laid up with a broken collar bone shortly after the ship sailed, making the other two men stand a watch and watch of six hours each. Steam was used to atomize or "pulverage" the oil but the installation served to show what could be done with oil and the trip was given much publicity. Meanwhile, the Italians, Austrians, and French were experimenting with oil in their men-of-war, though in most cases inefficient operation ensued from the use of steam for atomization. In December of 1897, and during the following month, an apparatus for burning fuel oil was installed on the torpedo boat *Stiletto* at the Navy Yard, New York, using a compressed air apparatus for spraying the oil. The purpose of the test was not so much to determine the increased evaporative value of fuel oil as to test its practical use. Heavy petroleum residue was used as fuel, petroleum by itself being generally considered too dangerous on account of its lighter volatiles.

Probably no single item of Naval engineering apparatus received greater scientific study and development than boilers. After Erics-

FIGURE 12



BELLEVILLE BOILER

FIGURE 12

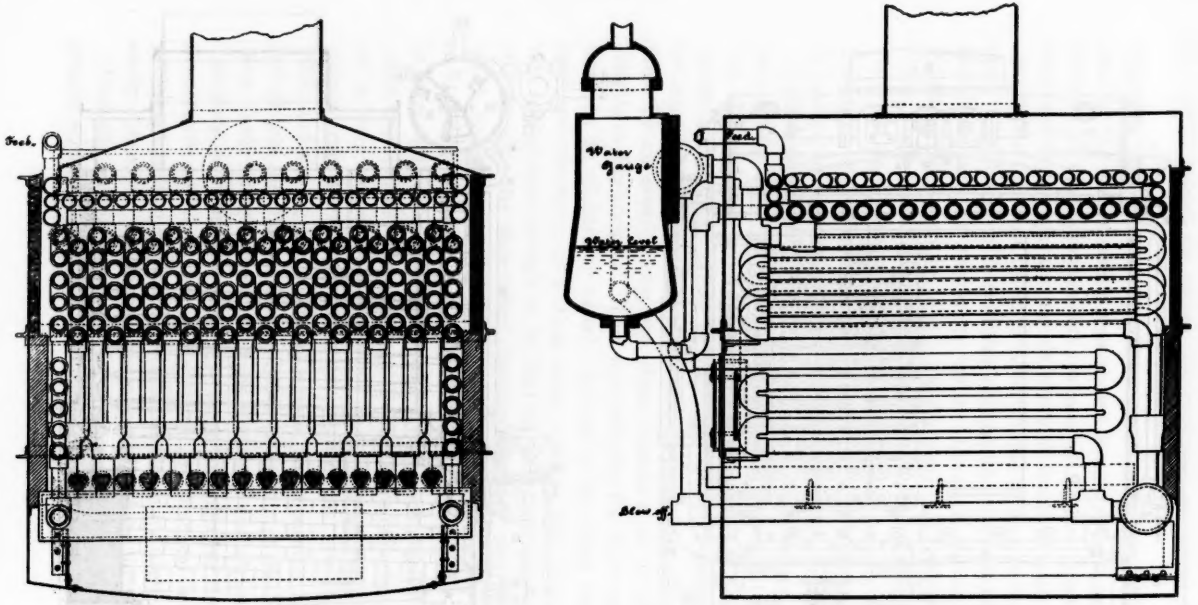
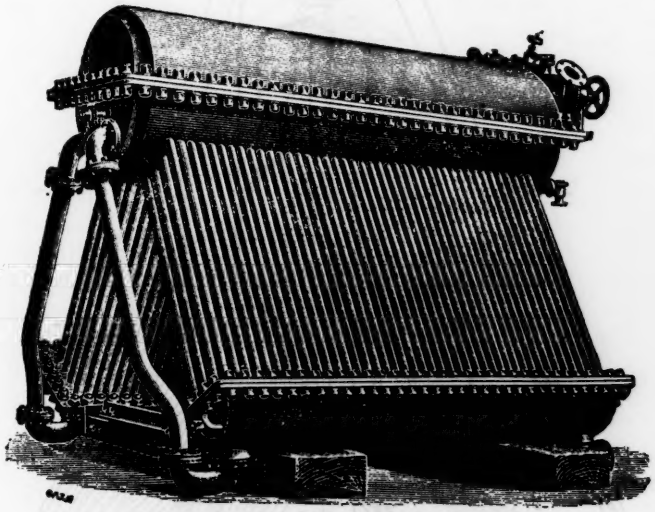


FIGURE 13

son's condenser in 1847 provided fresh water for boilers, iron began to replace copper in boiler construction. But the problem of corrosion arose, and several tests of boilers to destruction were made by a Mr. Stevens. The cylindrical fire tube boiler became the standard, though some elementary water tube boilers were used during the Civil War. Herreshoff, in building the torpedo boat *Lightning,* furnished our first true water-tube boiler, a coal burning, vertical type that operated somewhat on the flash principle. With the advent of higher pressures and the need for purer water, the

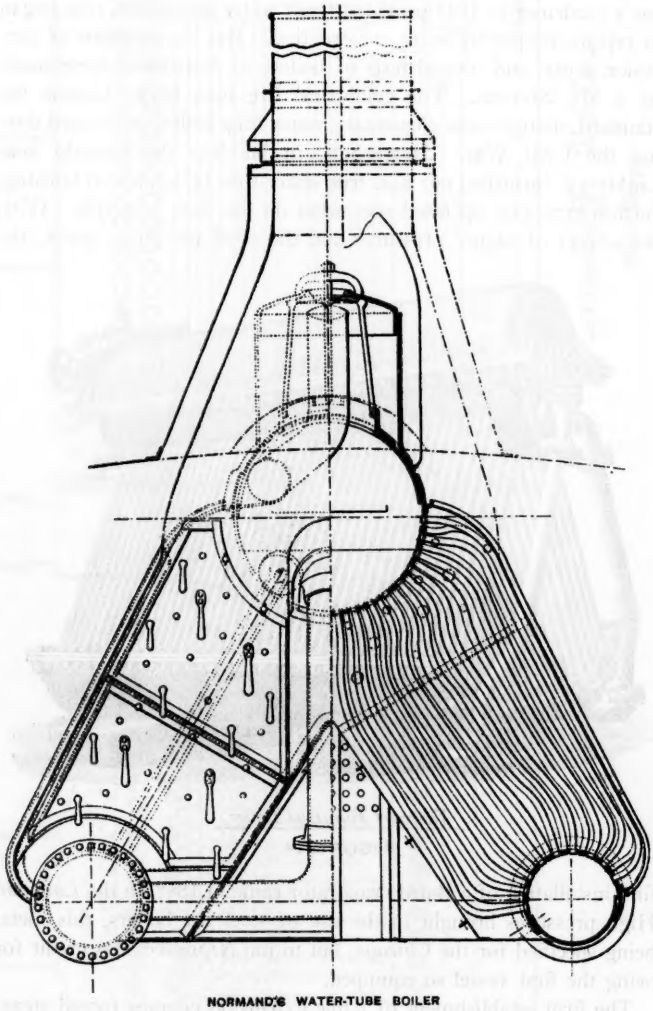


Yarrow's Tubulous Boiler.

FIGURE 14

first installation of a Baird evaporator came in 1882 on the *Lookout.* High pressures brought in the use of steel for boilers, this metal being specified for the *Chicago,* but to the *Nipsic* belongs credit for being the first vessel so equipped.

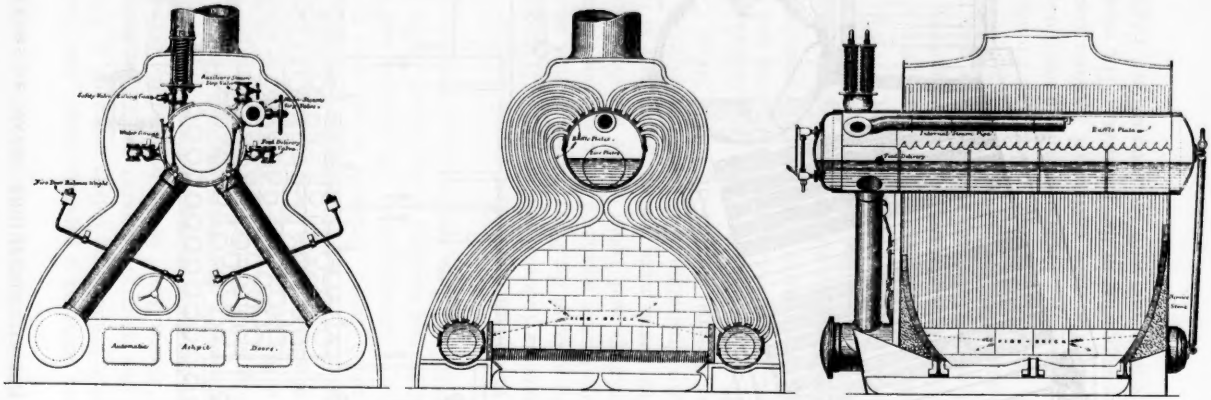
The firm establishment of triple expansion engines forced steam pressures still higher, and in 1888 the Navy Department invited competitive designs for coil boilers. Thornycroft in England, the



NORMAND'S WATER-TUBE BOILER

FIGURE 15

FIGURE 18



THE "THORNYCROFT" WATER-TUBE BOILER

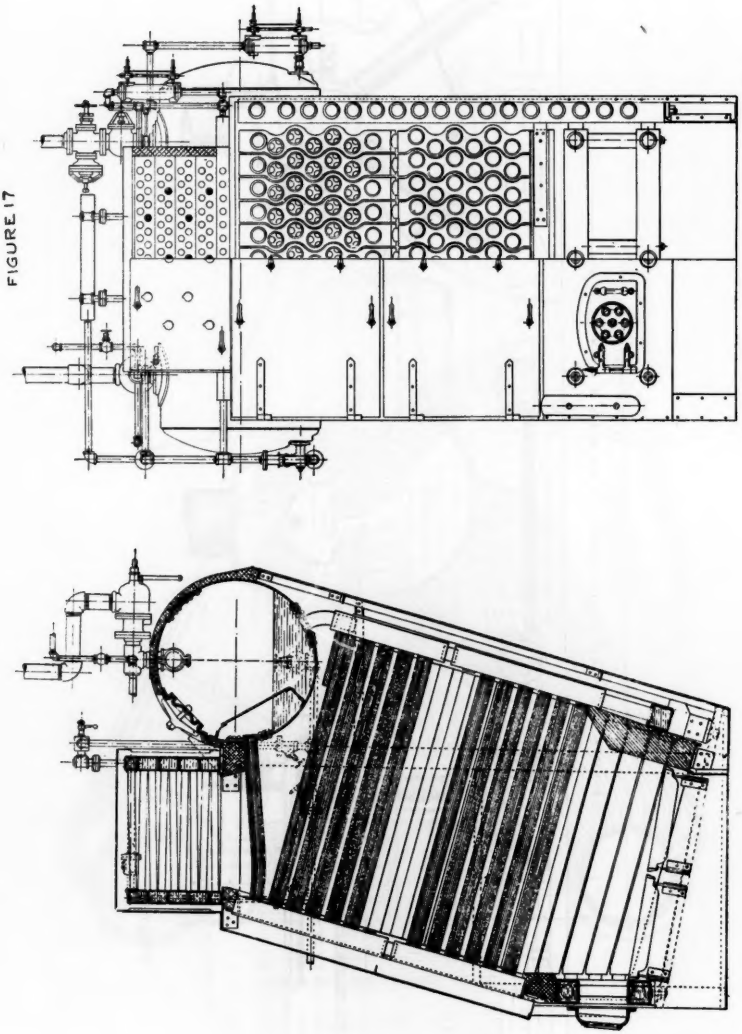


FIGURE 17

BABCOCK & WILCOX BOILER. TESTED AT ELIZABETHPORT, N. J.

following year, delivered a paper on water tube boilers for warships. Belleville header type boilers appeared in France, and one was tested in this country. Another water tube boiler with return bends and a "Steam Box" in the front of the boiler also had appeared. Following these designs, the *Cushing* boilers were changed to Thornycroft, and a few years later the *Dale* had water tube boilers operating at three hundred pounds pressure. Of considerable interest is the use of welded drums in the *Cushing's* boilers. A multitude of new designs (Figures 12 to 17) came into being, and into our service among them came the Normand, Mosher, Seabury, Ward, and Yarrow. Belleville boilers were rejected because of a general use of screwed joints. The Babcock and Wilcox boiler, for many long years a standard in the United States Navy, had its first tests in 1895, and these resulted in a decision to place them on the *Marietta*.

A feature that marked this first period was the rapidity with which developments followed one another. Magnolia metal, long an anti-friction metal in the Navy, passed its first successful test in 1888, aluminum bronze was tried but condemned because of blowholes in the castings, and Tobin bronze was developed by a Naval engineer. Other metals were studied, particularly as to their design applications. An illustration of this was the extensive tests made at the Watertown Arsenal for the Bureau of Steam Engineering in 1887 on the efficiencies and characteristics of riveted joints. The effect of temperature on metals, particularly iron and steel, was observed, forging temperatures being primarily considered. With this progress in mind it is not a surprise to find Past Assistant Engineer Bieg, U. S. N., recommending and urging in an article published in the August, 1895, JOURNAL, the building of a Naval Experimental Station near the Naval Academy for the purpose of both testing these new developments, and training cadet engineers.

In the field of pure science, advances were also rapid. Naval Constructor Taylor delivered papers on ship vibration and propulsion studies in this country while in England Froude was without a peer in the same field. Papers covering a multitude of scientific and practical subjects were exchanged between countries, many foreign articles appearing in the JOURNAL. The most outstanding event of the decade came with the International Engineering Con-

BABCOCK & WILCOX BOILER, TESTED AT ELIZABETHPORT, N. J.

gress held during the 1893 World's Columbian Exposition at Chicago. Engineer-in-Chief Melville directed the Division of Marine and Naval Engineering and Naval Architecture. Papers covering the entire field were gathered from the foremost authorities and were published in a large volume which today remains a classic. Isherwood had given considerable thought to high pressure steam in the face of statements by some engineers that the practical limit of pressure had been reached. DeLatour in France had calculated the critical temperature of saturation to be somewhere in the vicinity of 750 to 800 degrees Fahrenheit. This was not far wrong when we realize that after a series of careful experiments in later years a temperature of 705.4 degrees was finally established. Meanwhile the Naval service furnished to the various colleges engineers who served as professors of engineering. Many of these men resigned their commissions to devote their full time to teaching and to taking charge of the engineering colleges of the leading American universities.

One more scientific achievement may be added. The internal combustion engines appeared on the horizon in 1876, with the successful development of the Otto engine. While this engine ran and pointed the way to a new development, it still left much to be desired. Many bent their efforts to improving an engine that burned its fuel and developed power at the same time. Dr. Rudolf Diesel of Germany practically accomplished this in 1894 with his first engine. A larger engine was then built and placed in operation in 1896, the results being published in April, 1897, results that laid a basis for a revolutionary evolution in marine propulsion.

If the scientific field was active, the industrial field was even more so. Much of our present day machinery would not be possible had not machine tools been developed to a high degree of precision following the Civil War. Each improvement brought in larger and more accurate machines. Part of the industrial improvement was due to the Navy, the steel industry particularly benefiting. Steel had come into use slowly, Admiral Porter recommending its use for guns in 1870, and in 1881, steel was rolled at the Washington Navy Yard due to a lack of commercial facilities. The great impetus occurred in 1882, after a special board had recommended steel for the hulls of the new ships. At first only the hull steel was

of domestic manufacture, but in 1886 the specifications were changed to require all steel to be domestic, including forgings, thus forcing our shipbuilders to independence from foreign manufacturers. One further change in specifications occurred in 1891 when Bessemer steel was permitted, the field of supply being thus widened. Under these early specifications, the *Maine,* an armored cruiser, was the first vessel of steel in the United States Navy to slide down the ways. Steel castings early formed one of the products of the mills, early castings having a tensile strength of 40,000 pounds per square inch, though after failure of several castings for the *Maine* and contemporary vessels, improvement in casting technique was demanded. Many of the casting troubles were directly traceable to the drafting room, though by 1892 methods and quality had so improved that strengths of 60,000 to 70,000 pounds per square inch were customary. To the armor industry belongs credit for the advent of the alloy steels. Improvement in nickel steel armor plate brought to this country the concession that American armor was superior to foreign armor. Nickel steel shafting has been mentioned, while the JOURNAL in an early issue discusses the qualities of aluminum steel, chrome steel, copper steel, manganese steel, nickel steel, silicon steel, and tungsten steel. Further forging advance occurred in 1893 when the largest forging made in the United States was made for the Columbian Exposition Ferris Wheel. The shaft alone was 32 inches in diameter, and 45 feet long, with a hole 16 inches in diameter throughout its entire length.

Any discussion of shipbuilding during this period should not neglect foreign practice, for only through an exchange of ideas has any all-around improvement resulted. For example, the British placed their first triple expansion engines in the *Australia* and *Galatea* in 1887. With the British Navy the largest in the World, any improvement made by them was eagerly watched by other nations. Competition was keen among merchant vessels, almost every trans-Atlantic crossing being attempted for a record. In 1890, the *Teutonic* crossed in five days, nineteen hours, and five minutes, only to have the record broken two years later by the *City of Paris.*

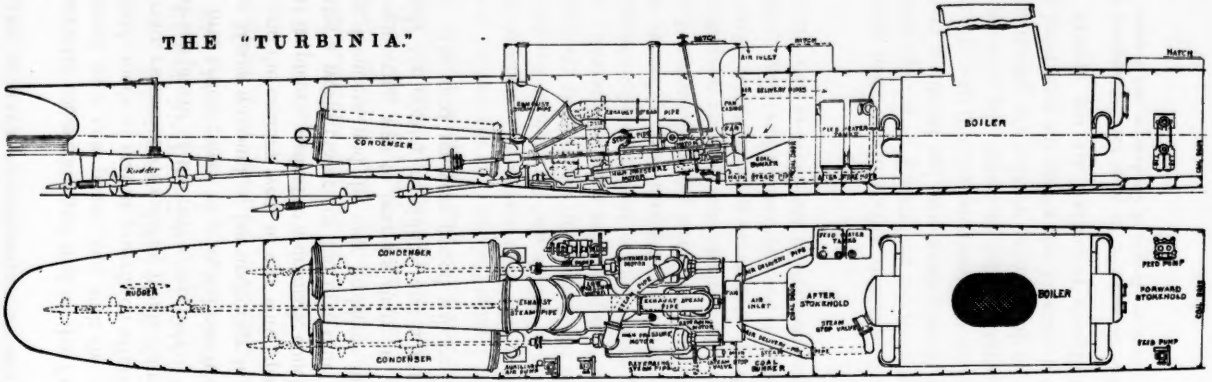
Again, torpedo boats formed a fertile field for experimentation, and the British *Daring,* after having modified Thornycroft boilers

installed in 1893, made 29.268 knots. Meanwhile, the firm of Yarrow had under contract two torpedo boat destroyers, the *Havoc* and the *Hornet,* one to have Yarrow locomotive boilers, the other Yarrow water tube boilers. Operation of these two plants under similar conditions was intended to furnish a basis of comparison. At the same time the French brought out a torpedo boat, the *Chavalier,* having two right-hand screws, and the rudder forward of the propellers. Aluminum also played its part, the French launching a yacht at St. Denis in December, 1893, with a hull of aluminum plate that had been rolled in France. Further torpedo boat experiments included the burning of oil refuse in the French torpedo boat *Surcouf* in 1893, and in the *Viborg,* the Russians held a series of liquid fuel tests which resulted in a determination to burn coal and oil in all torpedo boats furnished with locomotive boilers. The *Sokol,* powered by 8 Yarrow straight tube boilers, was the fastest vessel afloat in 1895. Other experimental or special purpose vessels were also built such as the "commerce protectors," *Powerful* and *Terrible* of the British in contrast to our "commerce destroyers." France, in addition to its aluminum yacht, built a gas engined scow in 1893. Shortly before, they had built a very shallow draft stern wheel gunboat which the Americans humorously stated "would run wherever there was a heavy dew." Looking over the long list of vessels building for foreign nations, two other types are worthy of note, one a shallow draft gunboat with special propeller tunnels for service on the Nile, and the *Vulcan,* designed and used as a torpedo depot ship and repair ship for servicing British torpedo boats.

Much stationary equipment was adapted to marine purposes. The English had early adapted the carbon dioxide compressor for refrigerating purposes and for fresh water, a Weir evaporator was used. In making technical advances, each nation seemed to share those of another, increments of improvement gradually being added except in those cases where a major change was made such as substitution of the water tube boiler for the cylindrical Scotch boiler. Sir Charles Parsons brought about the greatest change in 1897 with his *Turbinia,* a vessel that had been under development since 1894. On her trials she made a maximum speed of thirty-two and three-fourths knots at 2550 R.P.M., driving nine screws on three shafts. (Figure 18.)

FIGURE 18

THE "TURBINIA."



With the successful completion and trial of the *Turbinia,* Naval engineering entered on a new phase, and with the advent of the new and formidable mode of marine propulsion offered by turbines, the slow but certain extinction of existing plants commenced, urged on by a rapid development of the new competitor.

And so, our first article comes to a logical conclusion. In February, 1898, the *Maine* was sunk at her anchorage in the harbor of Havana, Cuba, and the country went to war with Spain. The war, naval in most of its phases, rushed to a dramatic conclusion, leaving the United States a world power for the first time in its history, with far distant frontiers, and the new problems incident to empire. Naval engineering was to bear its share in these with the insistent demands for greater reliability, and a greatly extended cruising radius. The next ten-year period will be discussed in a second article.

THE SPECTROGRAPHIC ANALYSIS OF CERTAIN MATERIALS TO DETERMINE THEIR CONFORMITY TO SPECIFICATIONS.

By Dr. Jacob Sherman [1] and Mr. W. J. Jeffries,[2] Member.

Although the spectroscope and the spectrum have been known and worked with continuously since Sir Isaac Newton's classical experiments over two hundred and fifty years ago, it is only recently that they have been applied seriously to commercial use in the analysis both qualitative and quantitative of the various metals appearing in the standard alloys. As the authors point out in this informative paper, the time ordinarily consumed in making the chemical analyses of metals and their alloys has become a serious item of delay in the delivery of materials as specification demands have become more precise, and industry generally more exacting. With more experience and a perfection of technique, the authors believe that spectroscopic analyses may ultimately largely replace chemical analyses for industrial purposes because less time is consumed in making the analysis, and upon its completion a file record of every test detail appears on a photographic plate. The Navy's first contribution to the experimentation now going forward in many laboratories throughout the world is here discussed.

Because of the important effects of deviation from a prescribed chemical composition, the performing of a large number of chemical analyses in Navy Laboratories has become a huge task and an expensive one from the standpoint of both time and cost. The cost is the least important factor, however, the principal consideration being accuracy in determining whether the percentage of the component parts of a material fall within the prescribed limits and also that those constituents proscribed are not present. Time is an

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important factor because of possible delay in acceptance of the material by the Government and consequent retardation of some phase of the construction program.

About two years ago serious consideration was given to this important phase of the inspection of Naval materials and means were sought to reduce the work load of the chemical laboratories. A symposium on spectrographic analysis held by the American Society for Testing Materials in 1935 indicated that the development of spectrographic equipment and methods of analysis had progressed to the point where some concrete results could be expected by the application of those methods to many of the routine determinations required by Navy Specifications. A spectrograph was purchased and installed in the Test Laboratory, Navy Yard, Philadelphia. While the spectrograph has thus far been of great value in reducing the time-volume ratio of chemical determinations the accuracy of the equipment renders it in no wise unsuited to research work of an important nature.

Chemical analysis of a material is desired for either of two reasons,

(*a*) In obtaining information as to the exact composition in order that the influence of its several constituents may be studied with respect to its physical characteristics and possible use.

(*b*) To determine conformation within prescribed limits set up by specifications. In most instances it is not necessary to know the exact percentage of an element present but it is very important to know if the maximum prescribed has been exceeded or that the minimum quantity required is present.

In the case of (*a*) information is desired as to the unknown constituents of a material in the process of development, or in the research into its technical or scientific uses. Usually not all relevant factors are known and therefore determinations of all minor as well as major constituents are carried out with the greatest accuracy and precision. On the other hand, in the case of (*b*) when the desirable composition has been established as within definite limits, the estimations for inspection purposes need not be as accurate or precise as in (*a*). It is sufficient to check conformity to predetermined limits and all that is required is a rapid, low cost and reliable method of assuring that conformity is a fact. A rapid and reliable method of determining minor constituents, sometimes

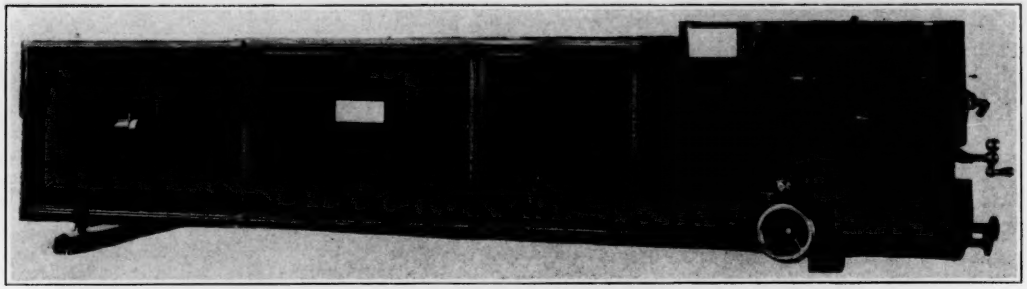

FIGURE 1.—LEFT SIDE VIEW.

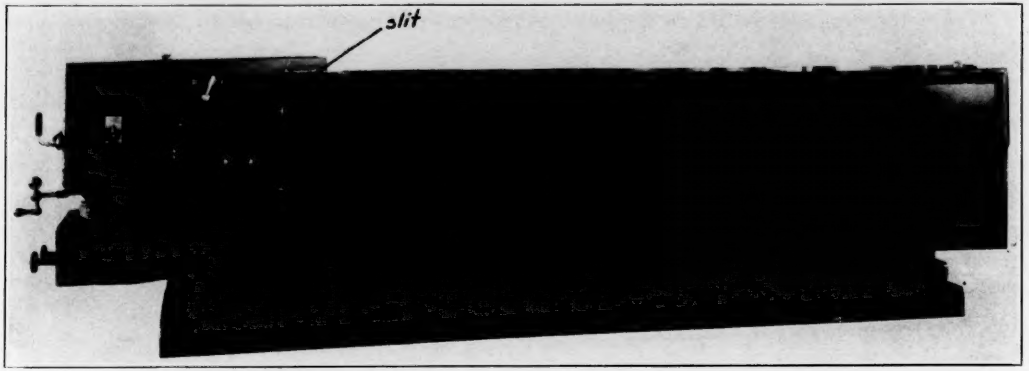

FIGURE 2.—RIGHT SIDE VIEW.

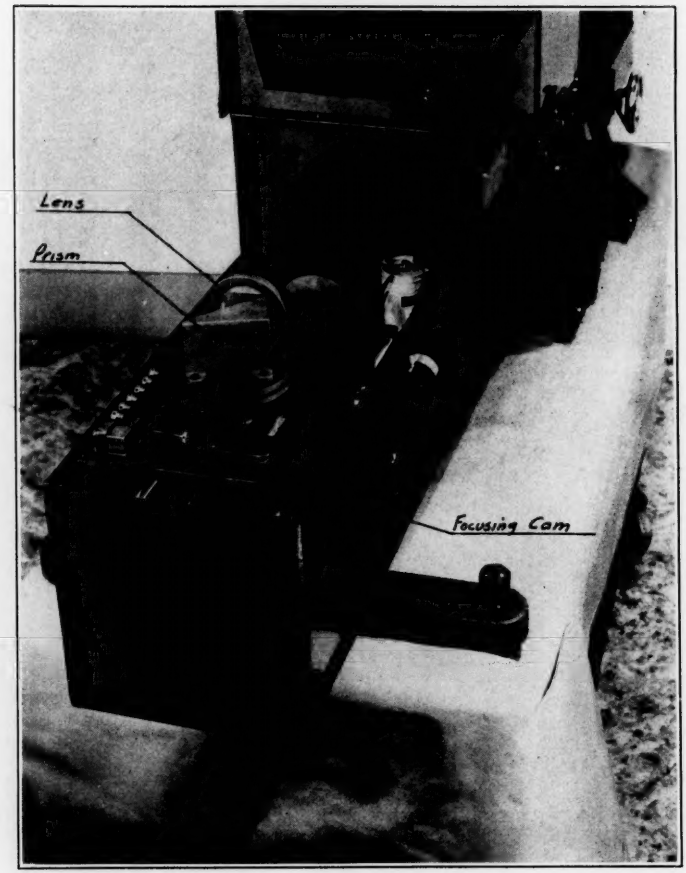

FIGURE 3.—THE LENS, THE PRISM AND THE FOCUSING CAM.

designated impurities, is especially valuable because of the great number of cases where the usual methods of chemical analysis are tedious and time consuming. Many analyses of metallurgical products for Navy use are in this class and this paper will show the advantage of the spectrograph for these kinds of materials.

Before discussing the main object of this article, a brief discussion of the theory of spectrographic analysis will be outlined in order that those who desire may go further into the fundamental considerations of spectrography. Radiation emitted by an incandescent source is of wave like character, an important associated function of which is $I(\lambda_j) \equiv$ the intensity of radiation of wave length λ_j. If we consider that portion of the radiation emitted by an incandescent gas, lying between λ_o and λ_1, then, only for a discrete finite set of values of λ_j $(\lambda_o \leq \lambda_j \leq \lambda_1)$ is $I(\lambda_j) > o$. That set $\{\lambda_j\}$ is characteristic of and uniquely determined by the chemical elements present in the incandescent source. The set $\{\lambda_j\}$ associated with any particular chemical element is called the *optical spectrum* of that element. Chemical elements which are metallic or metalloidal in character volatilize with incandescence and emit their characteristic spectrum when excited in the electric spark or arc.

In the Navy Yard Philadelphia Test Laboratory the radiation from an arc or spark source is analysed for its spectrum by a *prism* spectroscope. The radiation is brought into focus on a rectangular slit (about 10-20 microns wide). The radiation then passes through a collimating lens, onto a prism (either quartz or glass). The incident ray is deviated by transmission through the prism. The optical properties of the prism and construction of the system are such that the angle of deviation between the incident and transmitted ray (θ) is such a function of the wave length of the radiation under consideration that the angle is not constant, i.e., $\frac{d\theta}{d\lambda} \neq o \; (\lambda_o \leq \lambda \leq \lambda_1)$.

For the type of spectrograph in the Philadelphia Laboratory $\theta(\lambda)$ is also a decreasing function of λ_1, i.e., $\theta(\lambda_1) < \theta(\lambda_2)$, $\lambda_1 > \lambda_2$ where the equality sign does not enter. That is, the function is single valued, $\theta(\lambda_1) \neq \theta(\lambda_2)$, $\lambda_1 \neq \lambda_2$. This phenomenon is called dispersion.

The dispersed transmitted ray is then focused on a photographic plate, which, when developed, reveals a set of diffraction slit images or lines. As may be seen from the preceding paragraph, the distance between any two lines is proportional to the difference in wave length of the radiation causing the images. It is this line pattern, commonly though loosely, called the *spectrum*, which furnishes the basis for consideration in spectrographic analysis.

Qualitative analysis is made possible by determining the wave lengths of the rays recorded on the plate. Reference to sets of tables gives the elements associated with these lines. Quantitative analysis is made possible by measuring the relative optical density, roughly proportional to the blackness, of the line. Comparison with spectra of standard alloys or prepared correlation curves enable an estimation to be made of the concentration of the desired element. (It is tacitly assumed that for small amounts the relative intensity of a ray of given wave length is proportional to the relative concentration of the associated element present in the source.) The limitations of the method are apparent. Practically they are:

(*a*) Only metals and metalloids can be determined using the emission arc or spark spectrum.

(*b*) The upper quantitative limit, which varies from element to element, is about ½ per cent of the element sought and in some instances up to 5 per cent.

(*c*) The lower quantitative limit, which varies from element to element, depends very strongly on experimental conditions. For As it is about .01 per cent, while for Ag it is about .0002 per cent or less.

(*d*) The precision of a quantitative result is limited by the precision of an optical density measurement. This is a logarithmic function of a galvanometer deflection, and the best present limit is about 5 per cent of the amount present.

(*e*) Since the spectra are atomic in origin, only elements, not compounds, can be determined.

From the foregoing it is seen that the spectrograph is an optical instrument designed to break up the light from a source into its component wave lengths and to provide a means of qualitative and quantitative study of the spectrum thus formed. It is distinguished

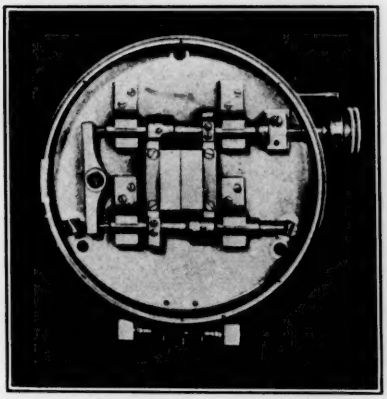

FIGURE 4.—SLIT WITH COVER REMOVED TO SHOW OPERATING MECHANISM.

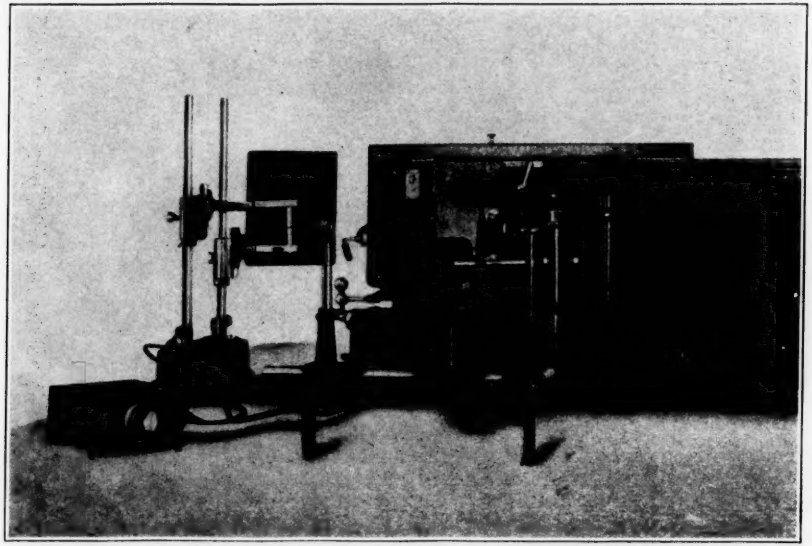

FIGURE 5.—COMPLETE ILLUMINATING SYSTEM, LARGE LITTROW SPECTROGRAPH. FROM LEFT TO RIGHT: ARC AND SPARK STAND, SPHERICAL CONDENSING LENS, ROTARY SECTOR DISC WITH MOTOR, CYLINDRICAL CONDENSING LENS.

from the spectroscope and spectrometer by its ability to record the spectrum photographically instead of visually. Basically the spectrograph consists of four essential parts in addition to the source of the radiation (the spark or arc)

(*a*) the slit
(*b*) the lens system
(*c*) the dispersing system
(*d*) the recording system.

Figures 1 and 2 are left and right views, respectively, of the Littrow spectrograph at the Navy Yard Test Laboratory. The illuminating system is not shown but the position of the slit is indicated. Figure 3 is a view showing the lens, the prism and the focusing cam. The lens system consists of a collimator and a camera lens. In the Littrow mounting (Philadelphia Laboratory) both functions are combined in one lens. The slit shown in Figure 4 is placed in the focal plane of the collimator and the recording system in the focal plane of the camera lens. Between the two lenses, or if only one lens is used, intercepting the ray of light between the two functions, is placed the dispersing system. In the Littrow mounting this consists of a thirty-degree prism of glass (or right or left quartz), with the light reversing its path through the prism.

The essential requirements for a good slit are

(*a*) the edges must be parallel
(*b*) the edges must be sharp and straight
(*c*) the slit material must resist corrosion and remain clean
(*d*) must be readily adjustable.

The recording system consists of a specially designed plate holder with a racking device to permit multiple exposure on one plate. Figure 5 shows the complete illuminating system, including the arc and spark stand (Figure 6), in which the sample is placed for volatilization.

The density comparator (Figure 7) consists of a projection system, a photo-electric cell for reception, a voltage regulator and a sensitive galvanometer mounted on a Julius suspension. Adjustments are provided in the optical system and a rack for moving the plate so that the desired line to be measured is over the slit cover-

ing the photo-electric cell. A spot of light reflected from the galvanometer mirror on a scale built into the instrument gives the reading which may be computed to optical units. Figure 8 is an optical diagram of the density comparator and is self explanatory.

The measuring microscope, Figure 9, is an instrument for accurately measuring the linear interval between the lines on the photographic record in order to compute accurate wave lengths. The microscope is attached to a heavy bed plate and means provided whereby the photographic plate can be moved in the focal plane. With this instrument measurements may be made within plus or minus .005 mm.

Figure 6 shows the setup of a specimen of aluminum alloy for sparking. It will be noted that the specimen rests on a piece of fiber of sufficient diameter to afford ample support. The upper electrode is lowered to contact the specimen and the lower electrode brought to within a predetermined distance to give a fixed spark gap. Solid specimens, rather than turnings are necessary but must be of suitable size and shape. The specimens used in this spark method at the Philadelphia Laboratory are about 2 inches long, ½ inch wide and about 1/32 inch or thicker, if practicable.

Spectrographic determinations are essentially short unit time operations. Spectrographic analysis in general should be accomplished in about one hour regardless of what elements are sought or in what combination or concentrations they are present. The actual time necessary to make the spectrographic exposure is from one to two minutes per sample; however, many exposures can be recorded on one plate. Figure 10 records sixteen (16) exposures. The difference between the one hour given above and the one minute exposure time per sample represents the time necessary for developing the negative and interpreting the results. Thus it will be seen that the actual time for each determination is less than two minutes for each sample analysed, when sixteen samples are run in rapid succession. This saving in time is a very useful characteristic of the spectrograph since experience has shown that the time-volume ratio of the spectrographic method is not more than 10 per cent of the chemical method. Chemical methods, as previously pointed out, are time consuming and nothing can be done to shorten the time. Then again there is a great difference in the time re-

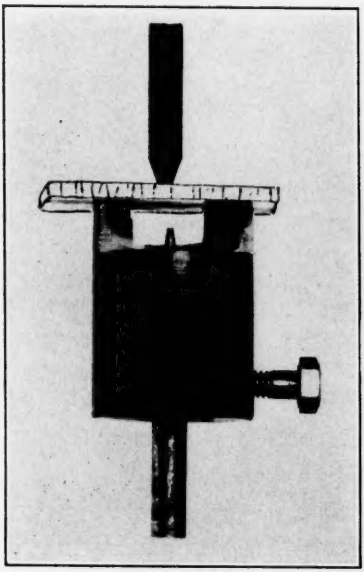

FIGURE 6.—SPARK STAND FOR VOLALITIZATION OF METALLIC SAMPLES.

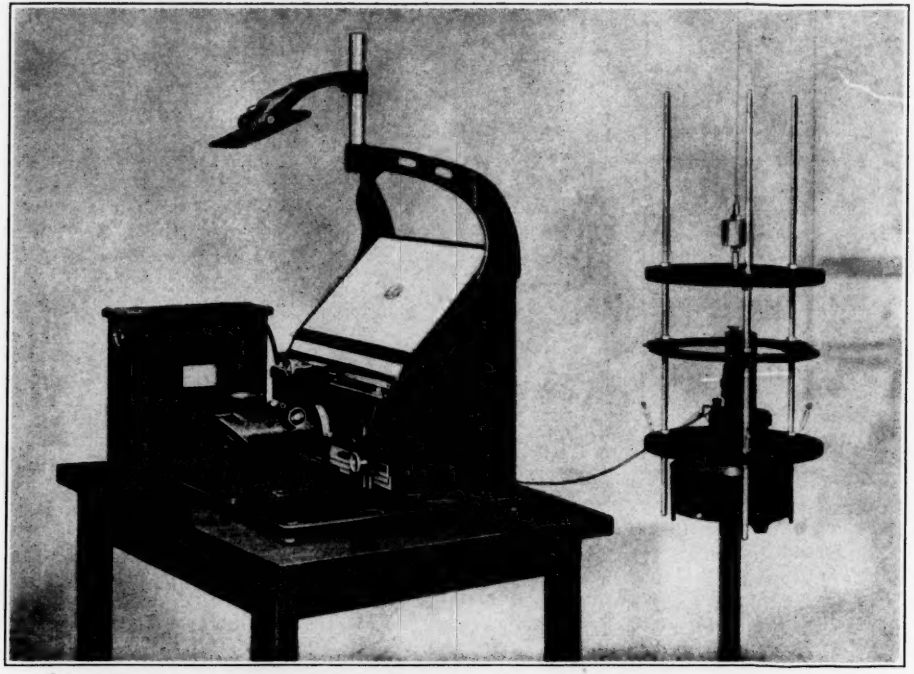

FIGURE 7.—DENSITY COMPARATOR WITH COMPLETE ACCESSORY EQUIPMENT MOUNTED AND CONNECTED FOR QUANTITATIVE WORK. ON THE TABLE IS THE DENSITY COMPARATOR WITH VOLTAGE REGULATOR, AT A DISTANCE OF ONE METER IS THE GALVANOMETER, MOUNTED ON THE JULIUS SUSPENSION.

quired for determining chemically any one of several elements. For example, carbon in steel can be determined in about twenty minutes whereas cadmium in zinc base die casting requires from five to seven working days.

There can be no question that, in general, for real accuracy and precision nothing is better than a carefully made chemical analysis. But, as was discussed in the introductory section, most analyses are made to determine conformity to specifications, and, as a rule in the great majority of instances, the ranges of allowable variation in composition are great enough to permit sufficiently reliable estimations using the spectrographic method. In any event, the chemical methods now used are of a nature suitable for routine analysis with expected deviation from absolute accuracy and precision. Again, in a chemical method, an unobserved accident, as a beaker boiling over, or the incorrect recording of a weight may yield misleading results. Using the same ordinary care, such results are highly improbable in the spectrographic method. One may get 1.9 per cent Mg where there is only 1.6 per cent, but one would never get 0.6 per cent instead of 1.6 per cent.

Even disregarding the time factor, a spectrographic analysis is much lower in cost than a chemical analysis. A photographic plate, 10 inches $\times$ 2 inches, costs \$0.08 and will record 10 exposures. Processing chemicals are comparatively inexpensive. It has actually been found that in the analysis of lead storage battery plates, the cost of materials used in the spectrographic method is only a small part of the cost of the filter paper usually used in the chemical method of analysis of that material. The only permanent feature in a chemical analytical procedure is the final record. A doubtful result can never be re-checked without repeating the entire procedure, and only then if the original sample is available. On the other hand, the spectrophotographic record is permanent and lasts for years. The plate requires very little space for storage and is instantly available for re-examination when required either to check a line density measurement or to observe whether any element had been overlooked. The field of application of the spectrograph at the Philadelphia Yard is quite broad considering the short time in which it has been in service. We will hereinafter give some of the applications so far considered successful. A list of Navy Department

ONE METER IS THE GALVANOMETER, MOUNTED ON THE JULIUS SUSPENSION.

Specifications for aluminum alloys is given in Table I showing for each alloy the element now analysed quantitatively by chemical and spectrographic methods. The elements usually sought are copper, iron, silicon, manganese, magnesium, titanium, nickel, chromium, zinc, and tin. In exceptional cases bismuth and lead must be determined. Since no spectrographic standards have yet been prepared for the latter two elements, they are determined by chemical methods. All of the other elements are determined spectrographically, if within the range referred to in a preceding paragraph.

TABLE I.

Navy Specification	*Grade or Class*	*By Chemical Analysis*	*Spectrographic Analysis*
43R5b	A		Complete
43R5b	B		Complete
43R5b	C	Copper	Balance
43R5b	D	Copper	Balance
43R5b	E		Complete
43S4	A & B	Copper	Balance
44T5c	A		Complete
44T19a			Complete
44T20	A		Complete
44T20	B		Complete
44T20	C		Complete
44T20	D		Complete
44T21a		Copper	Balance
44T22		Copper	Balance
44T28		Copper	Balance
44T30			Complete
44T31		Copper	Balance
44T32			Complete
46A1d	1	Copper	Balance
46A1d	2		Complete
46A1d	3	Silicon	Balance
46A1d	4	Copper	Balance
46A1d	5	Magnesium	Balance

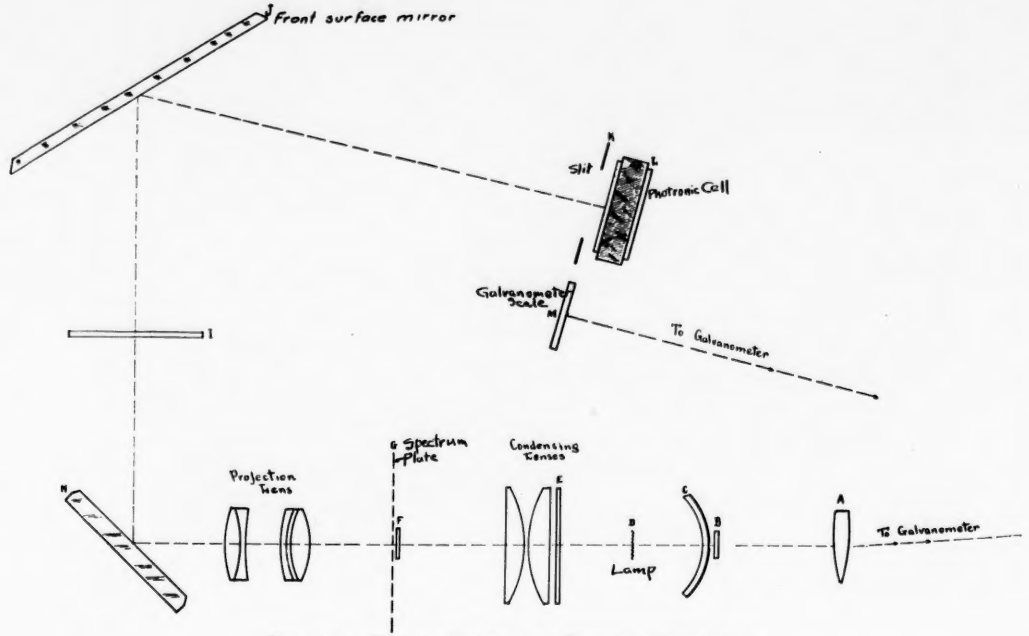

FIGURE 8.—OPTICAL DIAGRAM OF DENSITY COMPARATOR.

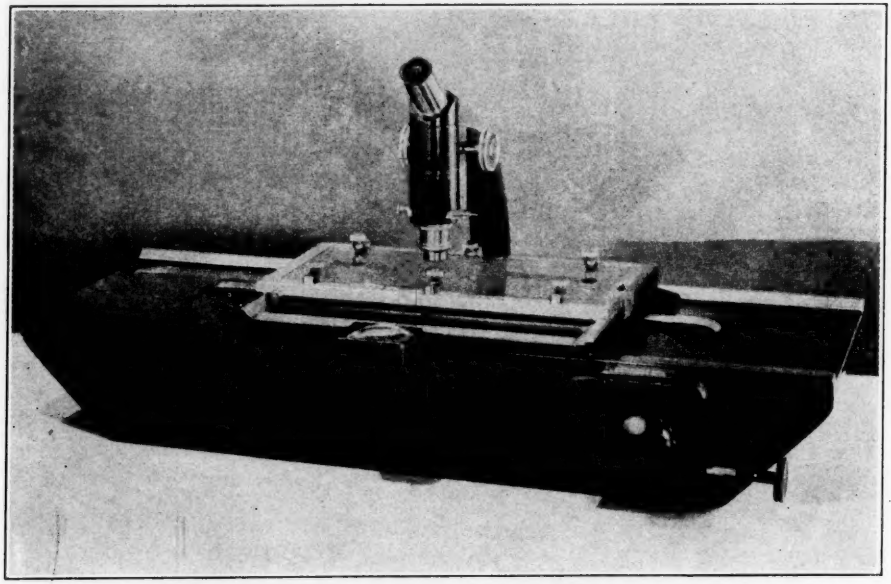

FIGURE 9.—SPECTRUM MEASURING MICROSCOPE.

TABLE I (Continued).

Navy Specification	*Grade or Class*	*By Chemical Analysis*	*Spectrographic Analysis*
46A2b	A		Complete
46A2b	B		Complete
46A2b	C		Complete
46A3c			Complete
46A4e		Copper	Balance
46A5c	1	Copper	Balance
46A5c	2		Complete
46A5c	3	Silicon	Balance
46A5c	4	Copper	Balance
46A5c	5	Magnesium	Balance
46A6d			Complete
46A7d	1	Copper	Balance
46A7d	2	Copper	Balance
46A7d	3		Complete
46A9		Copper	Balance
46A10a			Complete
46A11			Complete
46R1b	D		Complete
46R1b	E		Complete
47A2b			Complete
47A3b		Copper	Balance
47A4c			Complete
47A5b	Foil		Complete
47A6a	Al Clad	Copper	Balance
47A7			Complete
47A8a	Al Clad	Copper	Balance
47A10a		Copper	Balance
47A11			Complete
47A12a			Complete

In addition to aluminum alloys, spectrographic analysis is now being applied to the testing of lead battery plates. At the present time analysis of the plates is made entirely by spectrographic meth-

ods except for acid, moisture, arsenic and platinum in the active material. Lead and battery plate analysis can be reported the second day after receipt of samples. Zinc and zinc alloy die castings are now analysed by the spectrographic method with the exception of high aluminum in die castings. The spectrographic method saves considerable time and labor. By chemical analysis zinc spelter ordinarily requires three days and zinc base die castings from five to seven days. If no chemical analysis for aluminum is required zinc base die castings can be reported the same day as received or the day after.

For steel, spectrographic analysis can now be used to good advantage for determination of low percentages of copper, nickel, vanadium, molybdenum and chromium. Preparations underway are expected ultimately to result in the application of spectrographic methods to a large part of the analysis of future steel tonnage used by the Navy.

A very important consideration in the application of spectrographic analysis to the foregoing materials is the furnishing of suitable samples to the laboratory. It will be noted that in some instances complete analysis is made by the spectrographic method while in others one or more elements are determined chemically. In the former case a solid piece of the material is used as an electrode in the spark method while in the latter case as well as in the spectrographic arc method both a solid electrode and drillings are required.

Figure 10 is a record of sixteen exposures in the spectrographic analysis of sixteen samples of aluminum alloys required to be in accordance with the following specifications. This plate is intended to illustrate the difference in density between the quantities of the several elements when present. For example, exposure number 7 corresponds to number 7 of Table II. It will be noted that the magnesium and copper lines are very dense, the chromium lines are absent, the iron and silicon lines are faint and the manganese lines are of a medium density. On the other hand, exposure number 12 on the plate corresponding to number 12 of Table II shows the copper lines very faint, magnesium lines of medium density, the chromium lines present, the silicon line of medium density, the iron lines very faint and manganese lines absent.

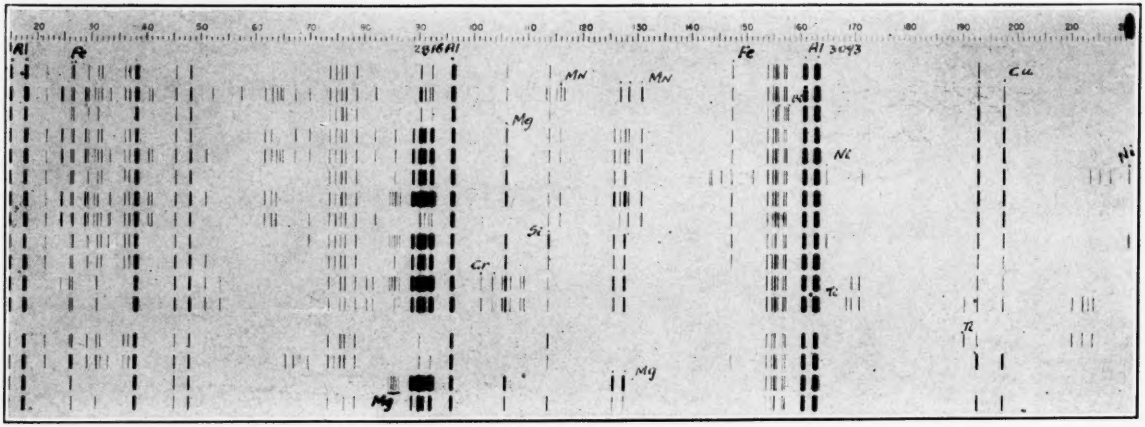

FIGURE 10.

TABLE II

Line	Specifications	Al	Cu	Fe	Si	Mn	Mg	Cr	Ti	Zn	Ni	Bi
1	472A	99.	.20	1.0		.05	.03			.03		
2	47A2	97.	.20	.70	.60	1.0	.03			.03		
						1.5						
3	Special											Present
4	Special											
5	47A3	92.	3.5	1.0	.75	.4	.20	.25		.03		
			4.5			1.0	.75					
6	Special										Present	
7	47A10	92.	3.6	.50	.50	.30	1.25	.25		.03		
			4.7			.90	1.75					
8	47A7	92.	3.0	.50		.4	.02					
	(Class 2)		5.0	1.2		1.2						
9	Special											
10	Special											
11	47A11*		.10	.45		.10	2.20	.15		.03		
							2.80	.35				
12	47A12*		.10	.35	45%		1.0	.20				
					60% of Mg		1.4	.30		.03		
13	46A5* (Class 2)		.10	.60	4.5	.03	.03		.20	.03		
					6.5							
14	46A5* (Class 4)		4.0	.30	.5	.03	.03					
			5.0		1.2							
15	46A5* (Class 5)		.10	.20	.25	.03	3.25					
							4.25		.20			
16	Special											

In order to check carefully the results obtained the laboratory has prepared about a score of "standard" aluminum alloys, within the range of the various compositions of specification limitations. Figure 11 is a spectrogram of one of these alloys showing the following composition:

Cu.	*Fe.*	*Si.*	*Mg.*	*Mn.*	*Sn.*	*Zn.*	*Al.*
.10	.50	.10	.05	.05	.05	.05	Remainder

* Balance.

At present the only steels analysed by the spectrographic method are the medium and high tensile structural grades. A spark spectrum is taken between two solid electrodes (slit 12 microns for 30 seconds). Only three of the constituent elements are determined by the spectrographic method at present. Development studies underway have for their object the analysis of all structural steels for Cu. Ni. V. Cr. Mo. Mn. and Si. In Figure 12 is shown part of the spectrum of a highly complex alloy steel in glass optics, showing lines due to Co. W. Mn. Cr. and V.

Pig lead and lead storage battery alloys are analysed in general by the spectrographic method adopted as tentative by the American Society for Testing Materials (ASTM designation E 25-35T). The complete analysis is made spectrographically and consists of quantitative determinations of Cu. Bi. Ag. Ni. Zn. Cd. As. Sb and sometimes Te. Figure 13 shows a qualitative spectrum of a lead alloy used in storage batteries showing the alloying elements present. The Figures showing the wave length are in Ångstrom units (1 Å = 10^{-10} Meter) Figure 14 shows quantitative spectra of lead storage battery plates. The spectra, reading from top down, shows alloys of the following composition:

	Fe.	*Cu.*	*Ag.*	*Bi.*
Standard No. 1	.05	.10	.010	.10
Standard No. 2	.02	.04	.004	.04
Battery Plate	.005	.01	.002	.045

It is obvious, of course, that the reproductions do not bring out all the detail or all fine lines on the photographic plate used for interpretation.

Zinc spelter and zinc base die castings are analysed (with the exception of aluminum present) by spectrographic methods adopted as tentative standard by the American Society for Testing Materials in 1935. The chemical composition of zinc base die castings is as follows:

Cu.	*Al.*	*Mg.*	*Fe.*	*Pb.*	*Cd.*	*Sn.*	*Zn.*
.03 Max.	3.5	.03	.10 Max.	.007 Max.	.005 Max.	.005 Max.	Remainder
	4.3	.08					

In addition to the above principle examples of the work now accomplished on a production basis, numerous other materials are

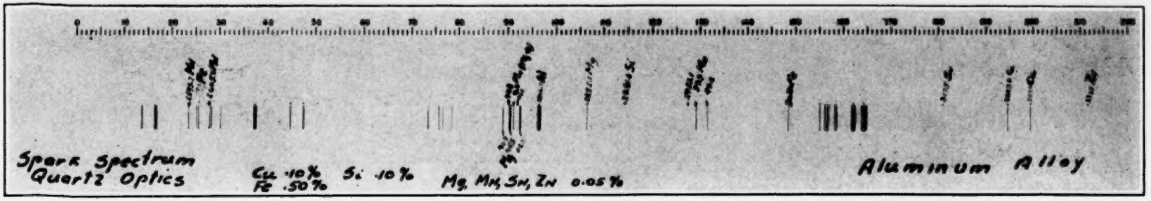

FIGURE 11.

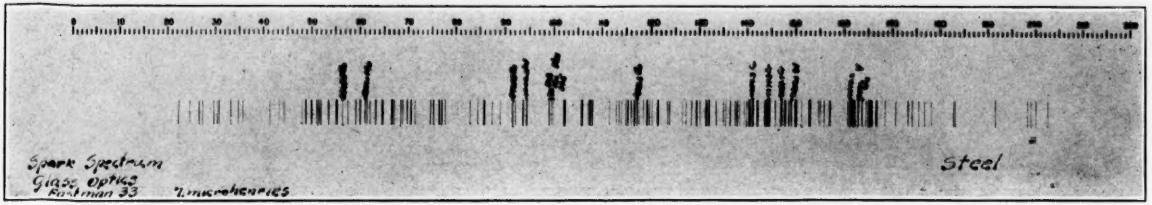

FIGURE 12.

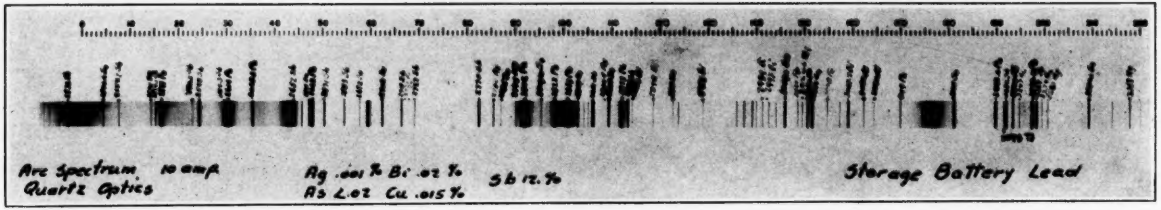

FIGURE 13.

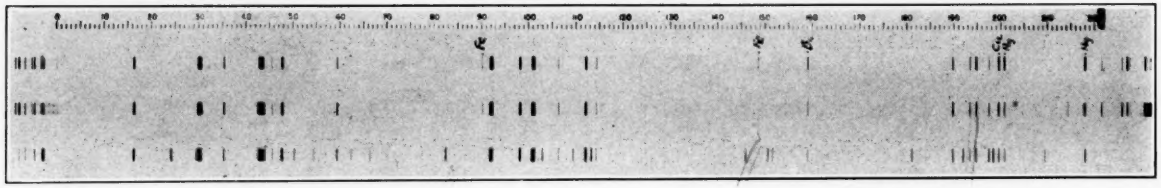

FIGURE 14.

analysed, at least in part, by the spectrograph. The list includes welding fluxes, fuel oil coke, magnet steel, cadmium-silver fuse wire and high purity chemical reagents. This latter application enables the checking of manufacturers labels for proscribed impurities in reagents to be used for precision chemical analysis and adds to the reliability of the results obtained in the use of those reagents.

The important extent to which the application of spectrographic methods of analysis in the inspection of Naval materials is used, has been but briefly shown. Moreover the great saving of time cannot escape notice and deserves especial consideration. The permanence of the record for rechecking without any further laboratory manipulation is a decided advantage over any sort of record of a chemical analysis possible. Although the method is new, increasing use by large industrial concerns in the control of their products is making important advances of frequent occurrence. Instances are more or less common, in which spectrographic analysis has revealed information impossible to obtain by chemical analysis. While the precision of a spectrographic result, in general, is not nearly as great as that of precise chemical analysis, it is quite satisfactory for the uses we have considered. Continued study will no doubt lead to greater precision in routine methods and open the door to wider applications. Although this story considers the important production problem of handling a large number of determinations, made necessary by Naval requirements at present, the value of the apparatus is not lost sight of as an instrument of research. The accuracy of a qualitative analysis of a metallic material for the detection of minute quantities, so far transcends the usual chemical methods as to place it in the forefront of modern developments. Moreover when this accuracy is associated with the element of time necessary in both methods, there appears to be no doubt that there will be a healthy acceleration of progress and a rapid increase in its use by analytical laboratories in routine testing. In conclusion the authors acknowledge the courtesy of the Bureau of Construction and Repair and the Bureau of Engineering for permission to publish this necessarily brief reference to the use of the spectrograph by the Navy. It is planned to supplement this paper by others, treating specific materials in more detail.

MATERIALS FOR HIGH PRESSURE-HIGH TEMPERATURE STEAM SERVICE.

By Lieutenant Commander Guy Chadwick, U. S. Navy, Member.*

The Design Engineer was in a hurry. He unrolled a drawing, spread it on the desk of the Materials Engineer and pointed.

Design Engineer. That piece will run pretty hot, and it must stand high pressure. What shall I make it of?

Materials Engineer. Grade A should do, but Grade B might be better.

D. E. How about welding?

M. E. You will have to use Grade C for welding, but that would require heat treatment.

D. E. Heat treatment would throw the whole works out of line.

M. E. Then use Grade D, but make it twice as thick.

D. E. Say, how long would it take you to collect all the information about materials for high temperatures?

M. E. About six months, but I am busy developing new information.

D. E. Shucks!

The Design Engineer returned to his board. He had neglected to mention scale resistance.

Recent phases of engineering development have resulted in the utilization of increased temperatures. The processing of petroleum products and the economical production of steam motive power furnish two well known examples of the use of progressively higher temperatures during the past two decades. As a result, it has become necessary for the materials engineer to investigate the characteristics of metals while under stress at high temperatures.

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This field of investigation proved to be enormous. Initial difficulties were presented by lack of basic data. New and intricate test equipment was required. Many promising leads proved blind. Short time tests gave doubtful results. Independent investigators arrived at differing conclusions. Technical literature became saturated with intricate expositions of isolated characteristics. Gradually, a limited amount of information was coordinated and various specifications were written giving physical and chemical values. But the selection of material for a specific application was left to the design engineer.

This method of selecting materials appeared reasonable, since the design engineer was familiar with the conditions of service to be met by the material chosen. At any rate, the materials engineer was busy completing his information.

Unfortunately, the great mass of information about stressed metals at high temperatures lacks availability. Application specifications are needed for ready reference by the design engineer. It is with this thought in mind that the following pages are presented.

SCOPE.

In order to prevent confusion, it is deemed advisable to limit the materials considered to those which are subjected to high mechanical stress and which derive their temperature from contact with or close proximity to steam at 650 degrees F. and above. In steam plants of normal design, the main parts to be considered are:

Steam pipes.
Steam pipe flanges.
Flange bolts.
Valves and fittings.
Boiler superheater drums and headers.
Boiler superheater tubes.
Turbine casings.
Turbine rotors.
Turbine blades.
Turbine nozzles.

WARNING.

In recommending materials for the services outlined above, we fully realize various dangers that lie in a realm which has neither

been explored by exhaustive laboratory tests nor posted by extensive practical experience. But high temperature steam plants will be built regardless. "The best is the enemy of the good." Therefore, we will do as well as we can and leave the best for tomorrow.

Nevertheless, in spite of the boldness of our approach, it appears necessary to forewarn the design engineer of certain general precautions to be observed in selecting materials from the data to follow for high temperature service.

1. The design engineer must have in mind all conditions of service and processes of fabrication to which the material is to be subjected.

2. The physical and chemical characteristics of furnace heats of metals vary, even with the most careful control of raw materials, melting time, and furnace temperature. Grain size, degree of oxidation, and heat treatment may differ for the same brand of metal. At high temperatures the effect of these variations becomes greatly accentuated. Cases have been noted where vital physical characteristics in carbon steel vary 200 per cent between heats. Alloy steels are ordinarily better controlled, but still show a tendency to vary.

3. A small difference in operating temperature may have a marked effect on physical properties. For example, in the high temperature operating range of a particular steel, a rise in temperature of 15 degrees may result in a drop of 25 per cent in creep strength.

4. Special attention must be afforded materials used in combination. Variations with temperature of expansion coefficients as well as special characteristics of dilatometer curves should be studied. Weldability is of concern.

5. The design engineer must be careful not to misuse new information to bolster up preconceived ideas. Rather, he should keep an open and questioning mind.

DEFINITIONS.

In developing a new technical field there is a temptation to indulge in moments of vagueness in order to bridge over such gaps as may appear in the landscape of information. Although we have admitted previously the incomplete character of information about

high temperature metals, it appears that definitions of certain terms will assist in resisting the tendency toward lax statements. These definitions also will furnish a better coordination between the thoughts of the writer and those of the reader.

While various standard publications have been consulted in determining the definitions, it has been thought advantageous to inject certain modifications which will fit more definitely the purposes of this article.

1. *Tensile strength.* The maximum tensile load which a material is capable of withstanding, measured in pounds per square inch of original cross-section.

2. *Yield point.* The tensile load at which a marked increase in length occurs without appreciable increase in load, measured in pounds per square inch of original cross-section. All materials do not exhibit a well defined yield point.

3. *Yield strength.* The tensile load which results in a specified elongation under load, measured in pounds per square inch of original cross-section.

4. *Proof stress.* The tensile load which, when released, will have resulted in a permanent elongation of 0.0001 inch per inch of gauge length, measured in pounds per square inch of original cross-section.

5. *Creep.* The gradual and continuous elongation or flow of a metal under stress at a given temperature.

6. *Creep strength.* The tensile load at a given temperature that will result in 0.1 per cent elongation in 10,000 hours, measured in pounds per square inch of original cross-section.

7. *Reduction in area.* The difference between least cross-section area after rupture under tensile load and the original cross-section area, expressed in terms of percentage of the original area.

8. *Percentage elongation.* The difference in gauge length at zero stress and the gauge length after rupture, expressed in percentage of the original gauge length.

9. *Modulus of elasticity.* The ratio of unit stress to unit strain, provided the unit stress does not exceed the elastic limit.

10. *Hardness.* (By the Brinell test.) Represented by an arbitrary number based on the diameter of the indentation imprinted

in a smooth surface by a 10 millimeter steel ball under a load of 3000 kilograms for 30 seconds.

11. *Impact resistance.* (Charpy.) The energy absorbed by a standard notched specimen when broken by a single blow of a standard pendulum or hammer, expressed in foot pounds.

12. *Coefficient of expansion.* (Mean, for a specified temperature range.) The increment change in unit length for a rise in temperature of one degree F.

13. *Endurance limit.* The maximum stress which may be repeated an infinite number of times without causing failure. The endurance limit for steels is usually measured at 10,000,000 cycles.

14. *Scale resistance.* The relative resistance to surface oxidation at high temperature, measured qualitatively.

15. *Dilatometer curve.* A graph showing linear thermal expansion during a heating and cooling cycle from room temperature through the upper critical range and return to room temperature.

16. *Heat treatment.* The development of desired physical properties by one or more controlled time-temperature cycles other than a simple anneal.

17. *Annealing.* Heating above the upper critical temperature range, followed by cooling at a rate to produce the softest condition of the material.

18. *Low temperature annealing.* Heating to a temperature below the critical, followed by slow cooling in order to reduce internal stresses.

19. *Normalizing.* Heating to approximately 100 degrees F. above the upper critical temperature range, followed by cooling in air at room temperature.

20. *Weldability.* (Metal arc.) The capacity to be subjected to the thermal effect of an electric arc without appreciable hardening or loss of toughness, and without developing flaws or discontinuities of structure at or near the weld boundary. Measured qualitatively by the temperature of preheat and of postheat or heat treatment necessary to obtain the desired properties.

21. *Hot work temperature.* The temperature range in which plastic deformation by mechanical working may be performed without resulting in a marked increase in hardness.

22. *Cold workability.* The capacity to withstand plastic deformation, usually at room temperature, and particularly in regard to the rolling and bending of tubes. Measured qualitatively by the relative effect on ductility.

CHOICE OF MATERIALS.

In reviewing the available metals for high temperature steam service, it appears that the design engineer must select a material of superior strength characteristics. Otherwise, he must be content with heavy sections to afford very low unit stress.

With this thought in mind, and after serious consideration, it was decided to eliminate the various carbon steels from the materials to be considered. It is recognized that carbon steel has been used successfully in various high temperature applications. But when temperatures exceed 650 degrees F., the suitability of carbon steel becomes progressively less until, at 900 degrees F. to 1000 degrees F. its usefulness is questionable.

There remain the alloy steels, particularly those containing molybdenum, either alone, or with other alloying elements. These steels, together with the 18 per cent chromium, 8 per cent nickel alloys, show favorable characteristics. Considerable data concerning their properties is at hand. No other field appears as promising at this time. Therefore, these materials have been chosen.

TABULATION.

Tables I to VI, inclusive, contain data covering thirty alloys. These are grouped in families of similar compositions. Tables VII and VIII cover an 18 per cent Cr.–8 per cent Ni. alloy. Since few comparative tests have been run by different agencies, it has been necessary to be extremely careful in choosing data. Unquestionably, some accurate figures have been discarded in the interests of safety. The figures given in the tables are believed to be conservative, and, in all cases, are backed up by some sort of test.

Table I lists data which identifies the various metals.

Tables II to V, inclusive, contain physical characteristics of the metals at 750 degrees F., 850 degrees F., 950 degrees F., and 1000 degrees F.

Table VI pertains to design, fabrication, and application.

TABLE I.

IDENTIFICATION DATA

No.	Ref.	Material	Chemical Composition, Percent												Heat Treated	Annealed	Physical Properties at Room Temperature					
			C	S	P	Mn	Si	Ni	Cu	Mo	Cr	V	W	Fe			Tensile Strength	Yield Strength	Proof Stress	Elong. in 2 in.	Red. of Area	Brinell Hardness No.	Impact Value Charpy
															Yes or No	Yes or No	Lb. Per Sq. Inch			Percent			Ft. Lb.
1	ERS	C-Mo Steel (Cast)	.22	.026	.029	.81	.43			.45					Yes		71850	50300	49600	29.4	51.6	149	30.7
2	ERS	C-Mo Steel (Wrought)	.18	.015	.012	.70	.12	.08	.10	.44					No	No	68250	47000	33500	31.0	59.5	146	
3	a	C-Mo Steel (Wrought)	.10	.030	.019	.62	.22			1.09							65175	46750		41.0	72.6	129	
4	b	Si-Mo Steel (Wrought)	.11				1.45			.50					Yes								
5	ERS	Cu-Mo Steel (Cast)	.18	.022	.025	.91	.37		.86	.18							86300	55500	50700	24.4	48.6	174	
6	ERS	Mn-Mo Steel (Cast)	.23	.012	.017	1.20	.30			.45	.08				Yes		71850	53900	38500	28.5	62.4	140	
7	c	Cr-Mo Steel (Cast)	.17			.82	.46			.74	1.08				Yes		80250	64500		25.6	56.0		19.5
8	ERS	Cr-Mo Steel (Cast)	.16	.018	.024	.58	.61	.26	.38	.70	1.10				Yes		109000	76650	69000	18.9	46.6	179	
9	ERS	Cr-Mo Steel (Cast)	.16	.018	.024	.58	.61	.26	.38	.70	1.10				Yes		67000	45000	44500	35.5	70.5	145	69.2
10	ERS	Cr-Mo Steel (Wrought)	.15	.022	.009	.78	.12	.04		.66	.96						98000	85000	75000	23.2	59.8	241	
11	ERS	Cr-Mo Steel (Wrought)	.14	.013	.013	.50	.52			.54	1.66				No	No	134500	92800	91500	23.5	59.0	255	60.4
12	ERS	Cr-Mo Steel (Wrought)	.43	.017	.016	.70	.43	.16		.60	1.80				Yes					14.0	37.3	334	
13	a	Cr-Mo Steel (Wrought)	.02	.012	.012	.53	.33			.39	1.05					Yes	72250	36000		34.0	73.3	134	55.0
	e	4-6% Cr Steel (Wrought)	Max. .25								4 to 6				Yes		95100	81140		28.0	71.5		
14	ERS	4-6% Cr-.5% Mo Steel (Cast)	.10	.011	.042	.57	.25	.64		.60	4.56						106750	84500	61250	16.5	38.2	212	
15	ERS	4-6% Cr-.5% Mo Steel (Wrought)	.11	.004	.010	.42	.04			.52	5.40				Yes		82850	57500	54250	32.5	70.6		19.8
16	a	4-6% Cr-.5% Mo Steel (Wrought)	.16	.015	.016	.36	.37			.58	5.13					Yes	75950	29200		33.5	69.3	183	85.0
																Yes	81500	41800		34.5	76.9	163	80.0
17	a	9% Cr-1.5% Mo Steel (Wrought)	.12			.38	.09			1.41	19.42												
18	b	Cr-V Steel (Wrought)	.40				.21				1.01	.17			Yes								
19	b	Cr-Si-Mo Steel (Wrought)	.07	.015	.014	.62	.72			.44	1.25					Yes	66500	34300		36.4	72.7	123	
20	b	Cr-Si-Mo Steel (Wrought)	.48	.015	.016	.59	.92			.52	1.60				Yes		97950	64650		28.5	48.9	197	
21	ERS	Cr-Mo-V Steel (Wrought)	.43	.011	.011	.34	.24			.41	.90	.20					141000	111000	107000	20.0	54.4	302	
22	b	Cr-W-Si-V Steel (Wrought)	.42				.77				1.40	.25	.98		Yes								
23	ERS	Si-Cr-Mo Steel (Cast)	.30	.020	.021	.53	.21	1.67		.23	.82						106500	91500	91000	22.2	58.4	212	
24	ERS	Ni-Cr-Mo Steel (Wrought)	.43	.015	.013	.62	.28	1.65		.26	.91				Yes		178250	167000	161500	16.5	54.4	363	
25	ERS	Ni-Cr-Mo Steel (Wrought)	.33	.015	.011	.62	.26	1.65		.26	.91				Yes		140500	132000	131500	21.9	65.6	277	46.2
26	ERS	Ni-Cr-Mo Steel (Wrought)	.43	.015	.013	.62	.28	1.65		.26	.91				Yes		122500	66800	52000	21.1	53.3	265	52.7
27	a	18% Cr-8% Ni alloy (Wrought)	Max. .07	Max. .030	Max. .030	Max. .80	Max. .75	18 to 19.6			16.5 to 19.6						91500	35600		63.0	58.0	156	90.0
28	a	16% Cr-13% Ni-3% Mo alloy (Wrought)	.07	.013	.010	.76	.35	11.84		2.66	16.79				Yes		90100	45000		48.8	65.7	156	76.0
29	a	12% Cr-20% Ni alloy (Wrought)	.10			.52	.97	21.45			24.96						100200	62180		33.0	62.5	175	80.0
30	ERS	76% Ni-14% Cr-8% Fe alloy (Wrought)				.39	.31	78.62	.14	.05	13.65			7.90			132000	111000	85250	15.0	16.4	274	

(a) Obtained from reference (a)

d Data obtained from reference (d) room temperature tensile strength = 90000 lb. per sq. in.

TABLE II.

PROPERTIES AT 750° F.

No.	Ref.	Material	Physical Properties				Creep Stress to Produce 0.1% Elong. in 10,000 Hours	Impact Value Charpy	Modulus of Elasticity	Thermal Linear Expansion	
			Tensile Strength	Yield Strength	Elong. in 2 in.	Red. of Area				Coefficient	Total
			Lb. per sq. in		Percent			Ft. Lb.	Lb. per sq. in X 10^6	Inch per Inch per Degree F.	Inch per Inch from 70° F. to 750° F.
1	KES	C-Mo Steel (Cast)	•68000	•28000	•25.2	•38.2	•27200		26.1	750° F. 7.0 X 10 - 6	.004760
2	KES	C-Mo Steel (Wrought)	•70500	•33200	•28.8	•52.2	•29200			750° F. 7.1 X 10 - 6	.004964
3	a	C-Mo Steel (Wrought)	•67000		•28.0	•66.5	♦32500			800° F. 8.0 X 10 - 6	.005440
4	b	Si-Mo Steel (Wrought)					♦25000				
5	KES	Cu-Mo Steel (Cast)					•28000			750° F. 7.1 X 10 - 6	.004828
6	KES	Mn-Mo Steel (Cast)					♦24000			750° F. 7.1 X 10 - 6	.004964
7	a	Cr-Mo Steel (Cast)	69400	41150	16.4	29.0	♦24000	17.5			
8	KES	Cr-Mo Steel (Cast)					♦14000				
9	KES	Cr-Mo Steel (Wrought)								750° F. 7.1 X 10 - 6	.004828
10	KES	Cr-Mo Steel (Wrought)									
11	KES	Cr-Mo Steel (Wrought)									
12	a	Cr-Mo Steel (Wrought)	•60500	•33800	•24.0	•67.0				802° F. 7.75 X 10 - 6	.005270
13	a	4-6% Cr Steel (Wrought)	•79000		•20.5	•77.0					
14	KES	4-6% Cr-.5% Mo Steel (Cast)									
15	KES	4-6% Cr-.5% Mo Steel (Wrought)								750° F. 6.6 X 10 - 6	.004488
16	a	4-6% Cr-.5% Mo Steel (Wrought)	•63500	•27500	•27.5	•66.0				1000° F. 7.0 X 10 - 6	.004760
17	a	9% Cr-1.5% Mo Steel (Wrought)	•68000		•33.0	•70.0				800° F. 6.67 X 10 - 6	.004535
18	b	Cr-V Steel (Wrought)									
19	b	Cr-Si-Mo Steel (Wrought)	71450	25450	27.0	57.8	♦24000				
20	b	Cr-Si-Mo Steel (Wrought)	89450	28750	31.0	62.3					
21	KES	Cr-Mo-V Steel (Wrought)									
22	b	Cr-V-Si-V Steel (Wrought)									
23	KES	Ni-Cr-Mo Steel (Cast)									
24	KES	Ni-Cr-Mo Steel (Wrought)									
25	KES	Ni-Cr-Mo Steel (Wrought)									
26	KES	Ni-Cr-Mo Steel (Wrought)									
27	a	18% Cr-8% Ni Alloy (Wrought)	•68500		•48.0	•68.0	♦27000			800° F. 10.06 X 10 - 6	.006854
28	a	16% Cr-13% Ni-3% Mo Alloy (Wrought)	•74000	•48500	•36.5	•65.0				800° F. 10.2 X 10 - 6	.006936
29	a	25% Cr-20% Ni Alloy (Wrought)	•86000		•34.0	•57.0				105 to 1320° F. 9.2 X 10 - 6	.006256
30	KES	78% Ni-14% Cr-8% Fe Alloy (Wrought)	d 85000		d49.5						

* Interpolated
♦ Extrapolated
d Data obtained from reference (d) room temperature tensile strength = 90000 lb. per sq. in.

TABLE III.

PROPERTIES AT 850° F.

No.	Ref.	Material	Physical Properties				Creep stress to Produce 0.1% Elong. in 10,000 Hours	Impact Value Charpy	Modulus of Elasticity	Thermal Linear Expansion	
			Tensile Strength	Yield Strength	Elong. in 2 in.	Red. of Area				Coefficient	Total
			Lb. per sq. in.		Percent			Ft. Lb.	Lb. per sq. in. X 10^6	Inch per Inch per Degrees F.	Inch per Inch from 70° F. to 850° F.
1	KES	C-Mo Steel (Cast)	•62700	•26500	•28.5	•44.3	20000		23.6	7.2 X 10 - 6	.005616
										850° F.	
2	KES	C-Mo Steel (Wrought)	•63300	•32000	•22.5	•54.0	22000			7.5 X 10 - 6	.005850
3	a	C-Mo Steel (Wrought)	•65300		•26.8	•67.0	•17000			800°F - 8.0 X 10 - 6	.006240
4	b	Si-Mo Steel (Wrought)					•13000				
										850° F.	
5	KES	Cr-Mo Steel (Cast)					15700			7.2 X 10 - 6	.005616
										850° F.	
6	KES	Ni-Mo Steel (Cast)					13300			7.4 X 10 - 6	.005772
7	c	Cr-Mo Steel (Cast)	79250	36550		45.0	24200	16.0			
8	KES	Cr-Mo Steel (Cast)					27000				
										850° F.	
9	KES	Cr-Mo Steel (Wrought)					17500			7.2 X 10 - 6	.005616
10	KES	Cr-Mo Steel (Wrought)	69500	21900		61.6	23000				
11	KES	Cr-Mo Steel (Wrought)	101250	67750	26.1	68.3	22500				
										802° F.	
12	a	Cr-Mo Steel (Wrought)	•56500	•33800	•29.5	•66.5				7.75 X 10 - 6	.006045
13	a	4-6% Cr Steel (Wrought)	•75000		•17.0	•75.0					
14	KES	4-6% Cr-.5% Mo Steel (Cast)	82800	69000	16.9	40.6	21000				
										850° F.	
15	KES	4-6% Cr-.5% Mo Steel (Wrought)					24000			6.7 X 10 - 6	.005226
										1000° F.	
16	a	4-6% Cr-.5% Mo Steel (Wrought)	•57000	•25250	•31.6	•69.5	∮22500			7.0 X 10 - 6	.005460
17	a	5% Cr-1.5% Mo Steel (Wrought)	•62500		•34.0	•72.5	∮35000			900°F - 7.0 X 10 - 6	.005460
18	b	Cr-V Steel (Wrought)									
19	b	Cr-Si-Mo Steel (Wrought)	•69000	•24000	•26.0	•66.0	•18500				
20	b	Cr-Si-Mo Steel (Wrought)	•75700	•27800	•31.2	•68.5	•15000				
21	KES	Cr-Mo-V Steel (Wrought)									
22	b	Cr-Si-V Steel (Wrought)					•17000				
23	KES	Ni-Cr-Mo Steel (Cast)					17000				
24	KES	Ni-Cr-Mo Steel (Wrought)					•17000				
25	KES	Ni-Cr-Mo Steel (Wrought)					17000				
26	KES	Ni-Cr-Mo Steel (Wrought)					•18200				
										600° F.	
27	a	18% Cr-8% Ni Alloy (Wrought)	•66000	∮15000	•42.0	•69.0	•21300			10.08 X 10 - 6	.007862
										800° F.	
28	a	16% Cr-13% Ni-3% Mo Alloy (Wrought)	•73000	•45250	•38.7	•62.0				10.2 X 10 - 6	.007956
										105 to 1320° F.	
29	a	25% Cr-20% Ni Alloy (Wrought)	•84000		•32.5	•55.7				9.2 X 10 - 6	.007176
30	KES	74% Ni-14% Cr-8% Fe Alloy (Wrought)	d 84000		d 49.0						

* Interpolated
∮ Extrapolated
d Data obtained from reference (d) room temperature tensile strength = 90000 lb. per sq. inch.

TABLE IV.

PROPERTIES AT 950° F.

No.	Ref.	Material	Physical Properties				Creep stress to Produce 0.1% Elong. in 10,000 Hours	Impact Value Charpy	Modulus of Elasticity	Thermal Linear Expansion	
			Tensile Strength	Yield Strength	Elong. in 2 in.	Red. of Area				Coefficient	Total
			Lb. per sq. in		Percent			Ft. Lb.	Lb. per sq. in X 10^6	Inch per Inch per Degree F.	Inch per Inch from 70° F. to 950° F.
1	XXX	C-Mo Steel (Cast)	-o- 56000	-o- 26000	-o- 27.5	-o- 52.0	11500		19.9	950° F. 7.1 X 10 - 6	.006424
2	XXX	C-Mo Steel (Wrought)	-o- 57500	-o- 31500	-o- 21.0	-o- 48.0	15000			950° F. 7.7 X 10 - 6	.006776
3	a	C-Mo Steel (Wrought)	* 60500		* 30.7	* 70.5	* 8000			1000° F - 8.4 X 10 - 6	.007192
4	b	Si-Mo Steel (Wrought)					* 7000				
5	XXX	Cr-Mo Steel (Cast)					* 7000			950° F. 7.8 X 10 - 6	.006336
6	XXX	Mn-Mo Steel (Cast)								950° F. 7.5 X 10 - 6	.006600
7	c	Cr-Mo Steel (Cast)	* 65000	* 32000	* 25.6	* 60.0		* 13.8			
8	XXX	Cr-Mo Steel (Cast)					* 15000				
9	XXX	Cr-Mo Steel (Wrought)								950° F. 7.2 X 10 - 6	.006136
10	XXX	Cr-Mo Steel (Wrought)									
11	XXX	Cr-Mo Steel (Wrought)									
12	a	Cr-Mo Steel (Wrought)	* 49500	* 31000	* 32.4	* 79.7	# 10000			1005° F. 7.81 X 10 - 6	.006873
13	a	4-6% Cr Steel (Wrought)	* 70000		* 16.0	* 73.6					
14	XXX	4-6% Cr- .5% Mo Steel (Cast)									
15	XXX	4-6% Cr- .5% Mo Steel (Wrought)					4300			950° F. 6.9 X 10 - 6	.006072
16	a	4-6% Cr- .5% Mo Steel (Wrought)	* 49500	* 22000	* 41.5	* 78.5	* 10000				
17	a	9%-Cr- 1.5% Mo Steel (Wrought)	* 58000	* 28250	* 36.0	* 77.5	* 14000			900° F. 7.00 X 10 - 6	.006160
18	b	Cr-V Steel (Wrought)					# 9000				
19	b	Cr-Si-Mo Steel (Wrought)	* 61500	* 23500	* 25.3	* 64.8	* 18000				
20	b	Cr-Si-Mo Steel (Wrought)	* 61500	* 25000	* 25.0	* 76.8	* 18000				
21	XXX	Cr-Mo-V Steel (Wrought)					27000				
22	b	Cr-W-Si-V Steel (Wrought)					* 19500				
23	XXX	Si-Cr-Mo Steel (Cast)									
24	XXX	Si-Cr-Mo Steel (Wrought)									
25	XXX	Si-Cr-Mo Steel (Wrought)									
26	XXX	Si-Cr-Mo Steel (Wrought)									
27	a	18% Cr-8% Ni Alloy (Wrought)	* 63000	* 14250	* 41.3	* 69.0	* 15000			1000° F. 10.2 X 10 - 6	.008976
28	a	16% Cr-13% Ni-3% Mo Alloy (Wrought)	* 71500	* 40000	* 40.6	* 58.5				1000° F. 10.5 X 10 - 6	.009240
29	a	25% Cr-20% Ni Alloy (Wrought)	* 82000		* 32.0	* 53.4				105 to 1320° F. 9.2 X 10 - 6	.008096
30	XXX	78% Ni-13% Cr-8% Fe Alloy (Wrought)	d 76000		d 45.8		# 25000				

* Interpolated
\# Extrapolated
-o- Extrapolated from tests made up to 900° F.
d Obtained from reference (d) room temperature tensile strength = 90000 lbs. per sq. inch.

TABLE V.

PROPERTIES AT 1000° F.

No.	Ref.	Material	Physical Properties				Creep stress to Produce 0.1% Elong. in 10,000 Hours	Impact Value Charpy	Modulus of Elasticity	Thermal Linear Expansion	
			Tensile Strength	Yield Strength	Elong. in 2 in.	Red. of Area				Coefficient	Total
			Lb. per sq. inch		Percent			Ft. Lb.	Lb. per sq. in. X 10⁶	Inch per Inch per Degree F.	Inch per Inch From 70° F. to 1000° F.
1	KKS	C-Mo Steel (Cast)								1000° F. 7.3 X 10 - 6	.006789
2	KKS	C-Mo Steel (Wrought)								1000° F. 7.8 X 10 - 6	.007254
3	a	C-Mo Steel (Wrought)	57190		32.0	73.5	5400			1000°F - 6.4 X 10-6	.007812
4	b	Si-Mo Steel (Wrought)					5000				
5	KKS	Cu-Mo Steel (Cast)								1000° F. 7.3 X 10 - 6	.006789
6	KKS	Mn-Mo Steel (Cast)								1000° F. 7.5 X 10 - 6	.006975
7	c	Cr-Mo Steel (Cast)	62400	30800	26.5	64.5		12.5			
8	KKS	Cr-Mo Steel (Cast)					7500				
9	KKS	Cr-Mo Steel (Wrought)								1000° F. 7.2 X 10 - 6	.006696
10	KKS	Cr-Mo Steel (Wrought)					♯ 6300				
11	KKS	Cr-Mo Steel (Wrought)									
12	a	Cr-Mo Steel (Wrought)	45200	29800	40.0	82.4	7000			1000° F. 7.81 X 10 - 6	.007263
13	e	4-6% Cr Steel (Wrought)	68500		18.0	75.1					
14	KKS	4-6% Cr-.5% Mo Steel (Cast)									
15	KKS	4-6% Cr-.5% Mo Steel (Wrought)					♯ 4000			1000° F. 7.0 X 10 - 6	.006510
16	a	4-6% Cr-.5% Mo Steel (Wrought)	45350		46.0	83.2	7200			1000° F. 7.0 X 10 - 6	.006510
17	a	2% Cr-1.5% Mo Steel (Wrought)	49300	24320	37.0	81.1	8500			1200° F. 7.1 X 10 - 6	.006789
18	b	Cr-V Steel (Wrought)					1400				
19	b	Cr-Si-Mo Steel (Wrought)	57750	21500	25.5	73.3	15000				
20	b	Cr-Si-Mo Steel (Wrought)	58000	22350	32.5	81.2	7800				
21	KKS	Cr-Mo-V Steel (Wrought)					1950				
22	b	Cr-W-Si-V Steel (Wrought)					13750				
23	KKS	Ni-Cr-Mo Steel (Cast)									
24	KKS	Ni-Cr-Mo Steel (Wrought)									
25	KKS	Ni-Cr-Mo Steel (Wrought)									
26	KKS	Ni-Cr-Mo Steel (Wrought)									
27	a	18% Cr-8% Ni Alloy (Wrought)	61600	14000	44.5	69.0	11500			1000° F. 10.2 X 10 - 6	.009486
28	a	16% Cr-13% Ni-3% Mo Alloy (Wrought)	70750	38000	39.5	58.3	14400			1000° F. 10.5 X 10 - 6	.009765
29	a	25% Cr-20% Ni Alloy (Wrought)	80450		32.5	51.4				1032° F. 10.6 X 10 - 6	.009858
30	KKS	78% Ni-14% Cr-8% Fe Alloy (Wrought)	d 72000		d 44.0		16000				

a Obtained from reference (a)
d Obtained from reference (d)
* Interpolated
♯ Extrapolated

TABLE VI.

No.	Ref.	Material	Oxidation Resistance	Fabrication Properties					Application
				Optimum Temp. Range for Hot Working	Cold Bending	Welding			
						Preheat	Relief Anneal		
				° F.		° F.	° F.	Hrs.	
1	KES	C-Mo Steel (Cast)	Resistance to oxidation and corrosion not appreciably different from carbon steel. Resistance to oxidation and steam erosion good up to 850° F.		120°	300 to 450	1200	¼	Suitable for applications where plain cast carbon steel is used, but where higher creep strength is required - steam valves, fittings, turbine castings
2	KES	C-Mo Steel (Wrought)			180°	300 to 450	1200	¼	Suitable for applications where wrought plain
3	a	C-Mo Steel (Wrought)			Yes	300 to 450	1200	¼	carbon steel is used but where higher creep strength is required - tubes, superheater headers
4	b	Si-Mo Steel (Wrought)			Yes	300 to 450	1200	¼	Applications similar to wrought C-Mo steel
5	KES	Cr-Mo Steel (Cast)			120°	300 to 450	1200	¼	Applications similar to ... cast C-Mo steel
6	KES	Mn-Mo Steel (Cast)			120°	300 to 450	1200	¼	Applications similar to cast C-Mo steel
7	a	Cr-Mo Steel (Cast)	Oxidation resistance intermediate		Yes	400 to 600	1200	¼	High temperature steam valves and fittings
8	KES	Cr-Mo Steel (Cast)	between C-Mo steel and 4-6% Cr-.5% Mo		Yes	400 to 600	1200	¼	
9	KES	Cr-Mo Steel (Wrought)	steel. Shows fairly good scale resist-		Yes	400 to 600	1200	¼	Superheater headers, superheater tubes
10	KES	Cr-Mo Steel (Wrought)	ance up to 950° F.		Yes	400 to 600	1200	¼	
11	KES	Cr-Mo Steel (Wrought)			180°	400 to 600	1200	¼	
12	a	Cr-Mo Steel (Wrought)				400 to 600	1200	¼	
13	e	4-6% Cr Steel (Wrought)	Oxidation resistance good at 950° F. and fair at 1200° F.	2150 to 2200	180°	600 to 800	1200	¼	Similar to 4-6% Cr-.5 Mo steel, but where good oxidation resistance with less creep strength is required.
14	KES	4-6% Cr-.5% Mo Steel (Cast)			Yes	600 to 800	1200	¼	High temperature steam valves and fittings
15	KES	4-6% Cr-.5% Mo Steel (Wrought)			180°	600 to 800	1200	¼	Superheater headers and tubes
16	a	4-6% Cr-.5% Mo Steel (Wrought)			180°	600 to 800	1200	¼	
17	a	9% Cr-1.5% Mo Steel (Wrought)	Oxidation resistance good at 1200° F.		Yes		1200	¼	For severe conditions where high corrosion resistance and good creep strength are required. Used in cracking still tubes
18	b	Cr-V Steel (Wrought)			Yes	Non-welding			High temperature bolt steel
19	b	Cr-Si-Mo Steel (Wrought)			Yes		1200	¼	Tube material and similar applications
20	b	Cr-Si-Mo Steel (Wrought)			Yes	Non-welding			High temperature bolt steel
21	KES	Cr-Mo-V Steel (Wrought)			Yes	Non-welding			
22	b	Cr-V-Si-V Steel (Wrought)			Yes	Non-welding			
23	KES	Ni-Cr-Mo Steel (Cast)	Oxidation resistance good at 850° F.,		Yes		1200	¼	High temperature fittings
24	KES	Ni-Cr-Mo Steel (Wrought)	fair at 950° F. Corrosion resistance		Yes	Non-welding			With lower carbon content for weldability appli-
25	KES	Ni-Cr-Mo Steel (Wrought)	not appreciably different from C-Mo		Yes	Non-welding			cation would be similar to material No. 23
26	KES	Ni-Cr-Mo Steel (Wrought)	steel		Yes	Non-welding			
27	a	18% Cr-8% Ni Alloy (Wrought)	Oxidation resistance for continuous service 1600° F. For intermittent service 1450° F. Corrosion resistance good	2100 S 1700 F	180°	Weldable			High pressure - high temperature service where high creep strength and excellent resistance to corrosion and oxidation are required. Tubes, soot blower elements, boiler casings, brick pans
28	a	16% Cr-13% Ni-3% Mo Alloy (Wrought)	Resistant to oxidation for continuous service up to 1600° F. Corrosion resistance good	2200 S 1700 F	180°	Weldable			Similar to 18 - 8 alloy but said to be more workable into seamless products by the usual piercing operations
29	a	25% Cr-20% Ni Alloy (Wrought)	Oxidation resistance for continuous service good for 2000° F. For intermittent service, 1900° F. Corrosion resistance good	2150 S 1800 F	180°	Weldable			Used where extreme resistance to oxidation is required. Soot blower elements, exhaust manifolds, stacks.
30	KES	75% Ni-14% Cr-8% Fe Alloy (Wrought)	Oxidation resistance good to 2000° F. Corrosion resistance good		180°	Weldable			Used for brick anchor bolts, soot blower elements and tubes

S - Start - maximum temperature.
F - Finish over this temperature.

Table VII shows physical properties of 18 per cent Cr.–8 per cent Ni. alloy at temperatures up to 1600 degrees F.

Table VIII shows creep stress values for 18 per cent Cr.–8 per cent Ni. alloy at temperatures up to 1500 degrees F.

The reference letters in the second column of tables I to VI, inclusive, denote the following sources:

E. E. S.—U. S. Naval Engineering Experiment Station, Annapolis, Md.

a—Technical Bulletin No. 6-B, 1936. (Corrected to date.) Digest of Properties, Carbon and Alloy Steels for Cracking—Still Tubes. The Babcock and Wilcox Tube Company, Beaver Falls, Pa.

b—Creep Characteristics of Metals by C. L. Clark and A. E. White. Trans. A. S. M. Vol. XXIV, No. 4, Dec., 1936.

c—Report on Bain Steel, April 2, 1934. The Edward Valve and Mfg. Co., Inc., East Chicago, Indiana.

d—Bulletin T-13, October, 1937. International Nickel Co., Inc., 67 Wall Street, New York, N. Y.

e—Corrosion and Heat Resisting Steels (Pamphlet). Crucible Steel Company of America.

Although the tables are designed for ready reference, they scarcely can be interpreted in their full sense without additional background. The selection of a metal is ordinarily a matter of compromise between the desired characteristics and those qualities available in the metal chosen. No single metal will have all the required qualities in the desired degree. Much thought must be given to the relative importance of the conditions of service. An intelligent understanding of the behavior of physical properties during fabrication and in service is essential. Therefore, these matters will be discussed.

LIMITING TEMPERATURES.

The type of application must receive consideration in determining the limiting temperatures for materials. As stated previously, high strength characteristics are of paramount importance in high pressure steam applications. The next most important point is the temperature where heavy scaling occurs.

The low and intermediate alloy steels show a decided decrease in their strength properties commencing at 950 degrees F. to 1000 degrees F. Therefore, 1000 degrees F. was decided upon as the upper temperature to be tabulated for these alloys. The high alloys show superior strength characteristics at higher temperatures as indicated by the separate tabulation of the 18 per cent chromium, 8 per cent nickel alloy.

Nevertheless, the limits herein considered should not be construed as prohibiting the use of the various materials under more moderate stress at higher temperatures. Where operating conditions are suitable, the following limiting temperatures may be considered.

C-Mo. Steel—Upper limit 1050 degrees F.

2 per cent-3 per cent Cr.-Mo. Steel—Upper limit 1100 degrees F.

4 per cent-6 per cent Cr.-Mo. Steel—Upper limit 1150 degrees F.

18 per cent Cr.-8 per cent Ni.; 25 per cent Cr.-20 per cent Ni.; 16 per cent Cr.-13 per cent Ni.-3 per cent Mo. Alloys—Pressure service to 1350 degrees F.

18 per cent Cr.-8 per cent Ni.; 16 per cent Cr.-13 per cent Ni.-3 per cent Mo. Alloys—Limited pressure service to 1600 degrees F.

25 per cent Cr.-20 per cent Ni. Alloy—Limited pressure service to 1800 degrees F.

Low and intermediate alloy tubes up to 9 per cent chromium have been in use at temperatures up to 1200 degrees F., mainly in the oil refining industry as furnace tubes.

CREEP.

At high temperatures, elastic deformation in metal is accompanied by plastic deformation. The plastic deformation proceeds at a slow rate within certain stress limits, and at the same time causes work hardening in the metal. This work hardening in turn prevents an increase in the rate of plastic flow.

It has been found convenient to pick an arbitrary standard limit for creep to be used in applications where creep characteristics are important. This has been set at 0.1 per cent elongation in 10,000 hours and is entered thus in the tables.

In examining time-extension curves showing creep under a constant load, it is seen that the initial rate of creep is relatively high; but at the end of 250 to 300 hours, the rate of creep will have decreased and thereafter will remain nearly constant. Since we are interested in long time creep values, it is evident that tests which do not run well past the initial period of changing rate into the period of constant rate are misleading. It is believed that creep data in excess of about 6000 hours actual test time is not yet available.

The design engineer, in using the tabulated values of creep strength, should consider these as limiting values and should not attempt to apply a factor of safety. However, he should consider also the tabulated temperature as a limiting temperature and be careful in checking his design to see that there is no place where the temperature exceeds this.

ENDURANCE LIMIT.

No considerable amount of fatigue data for cast steels is available and very few results for cast low alloy steels have been published. However, tests on wrought steels and on a relatively few cast steels show that the endurance limits (rotating beam and rotating cantilever) range from approximately 0.4 to 0.5 of the tensile strength. The latter figure (0.5) is probably applicable to the wrought low alloy steels. The former figure (0.4) is considered preferable for cast low alloy steels.

In applying the endurance limit to design, the following cases are cited:

1. For complete reversal of stress per cycle—Endurance limit equals 0.4—0.5 tensile strength.

2. For stress in one direction (as from zero to positive)—Endurance limit equals twice that for reversed stress or 0.8—1.0 tensile strength.

3. For completely reversed torsion—Endurance limit equals one-half that for reversed stress or 0.2—0.25 tensile strength.

4. For torsion in one direction—Endurance limit equals twice that for reversed torsion or 0.4—0.5 tensile strength.

5. For reversed cycles of unequal plus and minus intensity, the endurance limit would be a proportion of the values given above.

Thus for 80 per cent positive and 20 per cent negative reversed stress the endurance limit would be 0.64—0.8 tensile strength.

In all of these conditions, it is assumed that the elastic range will not be exceeded in design.

MODULUS OF ELASTICITY.

The modulus of elasticity for carbon and low alloy steels at room temperature is usually taken by design engineers as 29,000,000 pounds per square inch. Table IX shows the effect of temperature on the modulus of elasticity. It will be noted that the value at room temperature is 30,000,000 pounds per square inch. The figures in the table may be reduced to common practice by using a proportional value of 30 to 29:

TABLE IX.

VARIATION OF MODULUS OF ELASTICITY WITH TEMPERATURE OF CARBON STEELS.*

Temperature		*Modulus of elasticity lb.*
Deg. C.	*Deg. F.*	*per sq. inch* $\times 10^6$
20	68	30.0
100	212	29.2
150	302	28.6
200	392	28.1
250	482	27.5
300	572	26.9
350	662	26.2
400	752	25.2
450	842	23.7
500	932	21.1

The modulus of elasticity for Inconel at room temperature, according to the International Nickel Company is (1) elastic modulus 32,000,000 pounds per square inch, (2) torsional modulus 10,300,000 pounds per square inch.

* Geo. A. Arrok, Trans. Amer. Soc. Mech. Engrs., Vols. 49-50, 1927.

IMPACT TESTS.

It will be noted in the tables that impact values at high temperature are extremely meager. It is believed that for applications within the scope of this article the design engineer can assume ample impact resistance in all metals considered.

THERMAL EXPANSION.

In the tables, the coefficient of thermal linear expansion has been taken as the mean value over the specified temperature range. For example, Table II will show the mean coefficient of expansion between a room temperature of 70 degrees F. and the operating temperature of 750 degrees F. For the convenience of the design engineer an additional column has been placed in Tables II to V, inclusive, to show the total expansion from room temperature to operating temperature measured in inches per inch.

Since coefficients of expansion are not available in certain temperature ranges for all the metals considered, it has been necessary in several cases to assume values. Material No. 17, Table IV is one case. The mean coefficient of expansion from room temperature to 900 degrees F. is given as 7×10^{-6}. But the temperature range required by the table is 70 degrees F. to 950 degrees F. Thus, in computing the value of .00616 inches per inch for this latter temperature range, it was assumed that the same expansion coefficient held good for another 50 degrees. This assumption should lead to very little error. It will be noted that the same procedure has been used in other cases.

HOT WORKING TEMPERATURES.

The hot working temperatures for most of the alloy steels are not given in the tables. Forging and hot working temperatures are usually selected by trial methods. Hence, this information may be obtained best from those having experience in hot working a particular material.

The maximum forging temperatures recommended for safe practice in the case of carbon steels is 200 degrees F. below the solidus line of the Fe-C equilibrium diagram. This would be as shown in Table X.

TABLE X.

Per Cent Carbon in Carbon Steel	*Maximum Hot Work Temperature, Degrees F.*
0.10	2400
0.20	2375
0.30	2350
0.40	2325
0.50	2300
0.60	2250
0.70	2225
0.90	2150
1.00	2000
1.50	1900

In order to produce a fine grain structure in forgings, the finishing temperature should be only slightly above the critical range.

In general, the resistance of the carbon-molybdenum steels to rolling, forming and forging is greater than that of carbon steels, but less than that of chromium molybdenum steels. Carbon molybdenum steels can be worked hot or cold in a manner similar to carbon steels.

HEAT TREATMENT.

In nearly all cases, the metals considered for high temperature service should be heat treated in order to obtain the desired physical properties. This heat treatment may have to be varied between furnace heats of similar chemical analysis in order to obtain the specified properties.

The low alloy steels should be stress-relieved at 1200 degrees F. after welding. The 18 per cent Cr. — 8 per cent Ni. alloys are austenitic and require a water quench from 1950 degrees F. — 2050 degrees F. for an anneal. This treatment also is desirable after welding, but it is not ordinarily practicable to heat machine structures to such high temperatures. Under these conditions stabilized 18 per cent Cr. — 8 per cent Ni. alloy is indicated for welding. The 25 per cent Cr. — 20 per cent Ni. alloy, material No. 29 in the tables, also is austenitic and is annealed by a water quench from 2000 degrees F. — 2100 degrees F.

WELDING.

The weldability of a steel is modified by the preheat temperature required and the post-heat treatments applied after welding. The temperature of preheat and of post-heat is a measure of weldability. Those steels which do not require preheat or post-heat are considered the most readily weldable.

A carbon content of 0.20 per cent has been selected as an arbitrary dividing line for low alloy steels. Above this limit these steels should not be welded without preheating.

Carbon molybdenum steel is welded best by preheating at 300 degrees F. to 450 degrees F. as shown in Table VI. Preheating is particularly necessary when welding from one side only. Preheating is indicated especially when welding the chromium-molybdenum steels. The 4 per cent — 6 per cent chromium steel and Bain steel are not weldable unless preheated.

As an exception, small fittings usually can be welded without preheating.

All steels should be relief annealed after welding, if the carbon content exceeds 0.20 per cent.

Of course, weldability of any of the materials depends on suitable electrodes being available.

DILATOMETER CURVES.

Figures I to VI, inclusive, show the dilatometer curves of several metals. These curves are linear thermal expansion curves for a heating and cooling cycle. The expansion changes on heating and cooling are the manifestations of transformations taking place in the metal. The heating curve shows expansion. The cooling curve shows the presence of critical temperatures. In each case the specimen was heated above the upper critical temperature before cooling. Otherwise, the full differential between the heating and cooling cycles would not be shown.

It will be noted that some dilatometer cooling curves do not return at low temperature and retrace the heating curves. This phenomenon results from scaling at high temperature with a consequent loss of section and, therefore, increased extension under a given load. Tests in a gaseous atmosphere improve this aspect. The more consistent curves were derived from a specimen in carbon dioxide. A nitrogen atmosphere would yield better results.

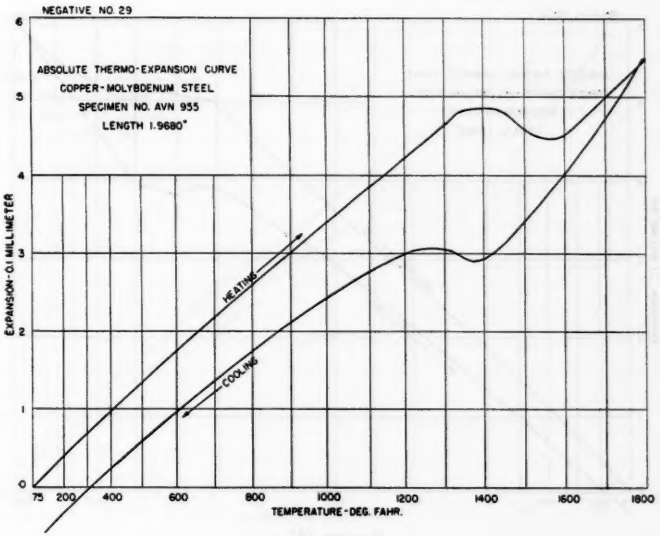

FIGURE I.

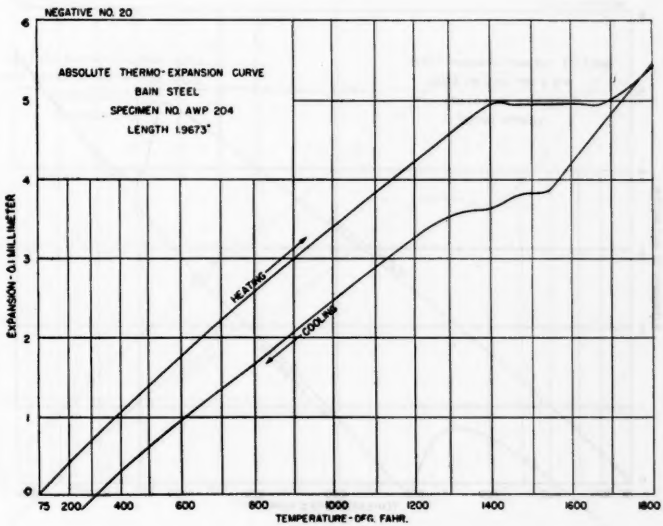

FIGURE II.

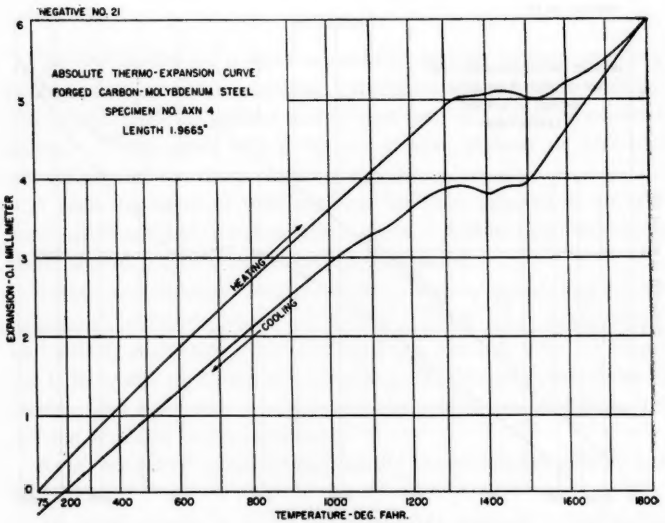

FIGURE III.

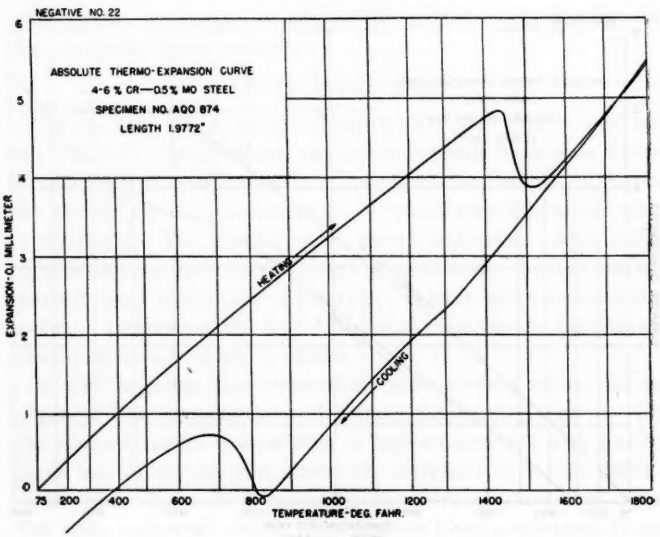

FIGURE IV.

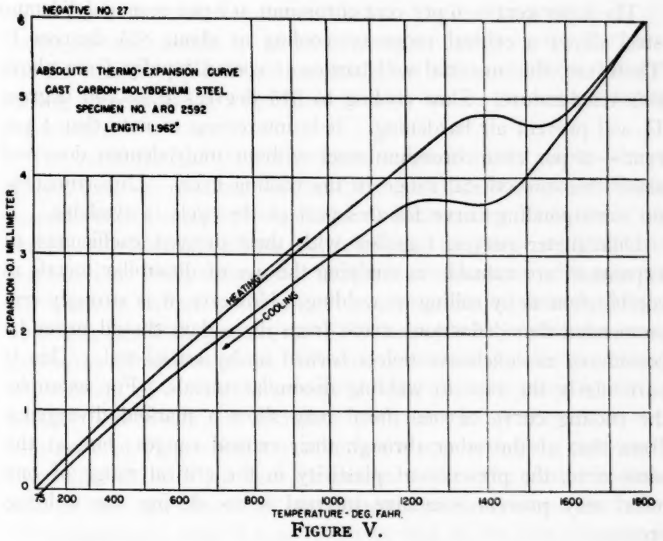

FIGURE V.

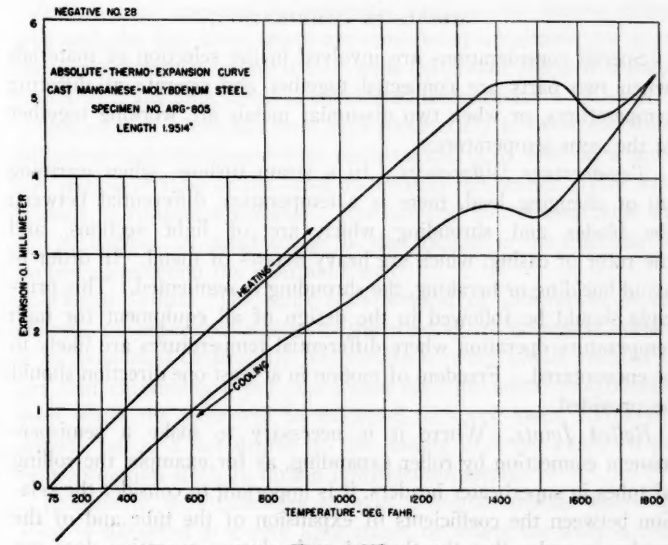

FIGURE VI.

The 4 per cent — 6 per cent chromium, 0.5 per cent molybdenum steel shows a critical range on cooling at about 825 degrees F. Therefore, this material will harden if cooled rapidly from above this temperature. Slow cooling to 675 degrees F. — 700 degrees F. will prevent air hardening. It is interesting to note that 4 per cent — 6 per cent chromium steel without molybdenum does not show this low critical range in the cooling cycle. Unfortunately, no corresponding curve for this part of the cycle is available.

Dilatometer curves, together with their derived coefficients of expansion, are valuable in studying the use of dissimilar metals in combination as by rolling or welding. However, it is strongly recommended that deductions made from these data should never be considered as conclusive unless backed up by actual test. This is particularly the case in welding dissimilar metals. For example, the cooling curve of one metal may show a marked divergence from that of the other through their critical ranges; but, at the same time, the presence of plasticity in the critical range of one metal may prevent excessive internal stress during the welding process.

METALS IN COMBINATION.

Special considerations are involved in the selection of materials when two parts are connected together and operate at differing temperatures, or when two dissimilar metals are working together at the same temperature.

Temperature Differences. In a steam turbine, when warming up or changing load, there is a temperature differential between the blades and shrouding which are of light sections, and the rotor or casing, which are heavy masses of metal. In order to avoid buckling or breaking, the shrouding is segmented. This principle should be followed in the design of all equipment for high temperature operation where differential temperatures are likely to be encountered. Freedom of motion in at least one direction should be provided.

Rolled Joints. Where it is necessary to make a semi-permanent connection by roller expanding, as for example, the rolling of tubes in superheater headers, it is important to consider the relation between the coefficients of expansion of the tube and of the header in order that the thermal cycle during operation does not

cause the rolled joint to come adrift. The safest method is, of course, to use metals of identical chemical analysis for the tube and the header. When this practice is not followed a tube material having a coefficient of expansion close to that of the header should be selected.

The tabulation of thermal expansion given in the tables shows that, among the iron base alloys, there are only three major classes of materials in regard to coefficient of expansion. First, there are carbon molybdenum, silicon molybdenum, manganese molybdenum, and low alloy steels containing chromium not in excess of 2 per cent. All of these have a coefficient of expansion approximately 7.5×10^{-6} inch per inch per degree F. The second classification comprises the chromium alloys, with and without molybdenum, having a coefficient of expansion perceptibly less than the other low alloy steels. The coefficient decreases with increasing chromium content until, at 27 per cent chromium, it is approximately nine-tenths the value of the 2 per cent chromium steel. The third classification includes the chromium nickel austenitic steels whose coefficient of expansion is about 1.4 to 1.5 times that of the low alloy steels.

Rolled joints between the austenitic steels of the chrome nickel type and the low alloy steels are considered unsuitable for high temperature service. The use of high chromium alloys in combination with low alloy steels is considered undesirable.

One method which has been used successfully to overcome these difficulties in boiler superheater construction, is to weld on a short end section of tube of the same material as the header. The weld is made by resistance welding. The stub end is protected from the fire by baffles. A disadvantage in this method is the difficulty of properly inspecting the resistance weld.

Welded Joints. The same consideration of differences in coefficient of expansion applies to the welding of dissimilar metals. It is considered particularly undesirable to weld metals such as 18 per cent chromium, 8 per cent nickel steel to carbon molybdenum steel where the joint will be subjected to heavy loads. This also applies, but to a less degree, to the joining of 4 per cent — 6 per cent chromium steels to carbon molybdenum steels.

Frequently, it is necessary to weld dissimilar metals where the joint is subjected to a very light stress, or where the weld is used

only to seal against leakage. Satisfactory welds in these cases can usually be made by the proper selection of electrodes, and by attention to such elements of procedure as preheating. For example, the welding of 18 per cent chromium, 8 per cent nickel steel to carbon molybdenum steel is accomplished by using a welding electrode having 23 per cent chromium, 8 per cent nickel in order to produce a ductile weld metal. The use of an electrode different in chemical analysis from both the base metals is to produce a deposit high enough in chromium and nickel to be austenitic in character. There is sufficient dilution of the weld metal by the carbon molybdenum steel to produce a brittle weld metal deposit, should an ordinary 18 per cent chromium, 8 per cent nickel welding electrode be used. When combinations of low alloy metals are welded, it is usually sufficient to employ an electrode normally required for the material of lower alloy content, preheating to the higher of the two temperatures specified for the respective base metals.

Maintenance of Clearances. The selection of materials for use in turbine rotors and turbine casings depends to a great extent on the creep properties of the metals. The unit stresses adopted for the design should be combined with high creep strength in order that the plastic expansion from creep will have a minimum effect on clearances. By the same token, metals having similar coefficients of expansion should be adopted for both the casing and the rotor.

Sliding Friction. A special requirement of materials at high temperature is involved in the selection of metals to operate in the slide and seat combinations of reciprocating pumps driven by superheated steam. Tests at the U. S. Naval Engineering Experiment Station indicate that it is desirable for one of the metals, preferably the seat, to be of cast iron, and that the other metal should be a heat treated 13 per cent chromium steel. Up to the present time, no satisfactory combination of steels has been found for this particular service. The tendency of cast iron to exhibit growth at high temperature must be considered in the design.

A similar type of service, although not so severe, is encountered in steam valve trim, for example, between the stem and the stem bushing. For this particular combination, a hardened 13 per cent chromium alloy is used for the stem, and the stem bushing is of a 55 per cent nickel, 30 per cent copper, 10 per cent tin alloy.

18:8 ALLOYS.

In order to present a more complete picture of the 18 per cent chromium, 8 per cent nickel alloys, Tables VII and VIII are included. These tables cover higher temperatures than the 1000 degrees F., limiting temperature of the main tables.

The chemical and physical property values of Table VII are taken from The Babcock and Wilcox Tube Company, Technical Bulletin No. 6-B, 1936. The creep values given in Table VIII have been taken partly from this bulletin. However, some of the values, particularly under the heading 1000 hours, have been modified toward the more conservative, additional information having been obtained from the A. S. T. M. and other sources.

The modulus of elasticity for the 18:8 alloy is 29,000,000 pounds per square inch.

TABLE VII.

*Tensile Properties for 18:8 Alloy**

Temp. Deg. F.	*Ultimate Strength*	*Elongation Per cent in 2 inches*	*Reduction of Area Per cent*
Room	91500	63.0	58.0
800	67025	45.2	68.8
900	64480	40.2	69.1
1000	61625	44.5	69.0
1100	53730	40.7	64.8
1200	44375	46.7	64.1
1300	35610	50.7	58.2
1400	23640	53.2	51.0
1500	17210	54.5	47.2
1600	14500	50.0	45.0

Carbon	.07 per cent max.
Sulphur	.030 per cent max.
Phosphorus	.030 per cent max.
Manganese	.60 per cent max.
Silicon	.75 per cent max.
Chromium	16.50 — 19.50 per cent
Nickel	8.00 — 10.50 per cent

* Babcock and Wilcox Tube Company Bulletin No. 6-B, 1936.

TABLE VIII.

*Creep Values for 18:8 Alloy.**

Temperature	*Creep stress in lb. per sq. inch for 0.1 per cent Elongation*	
Deg. F.	*1000 hours*	*10,000 hours*
800	.....	25000
900	20000	18000
1000	15000	11500
1100	8500	7100
1200	5500	4300
1300	3500	2500
1350	2500	1600
1500	800	750

4 PER CENT — 6 PER CENT CR. STEEL VERSUS 4 PER CENT — 6 PER CENT CR. — 0.5 PER CENT MO. STEEL.

Material No. 13 is a 4 per cent — 6 per cent chromium steel without molybdenum, whereas materials Nos. 14, 15, and 16 are of a similar type, but contain molybdenum.

Instances have been reported where the 4 per cent — 6 per cent chromium steels have shown temper brittleness after considerable service (about 2 years). Brittleness is reported to manifest itself at room temperature, as during a shut-down period. No such behavior has been reported for the 4 per cent — 6 per cent chromium, 0.5 per cent molybdenum steels.

COBALT CHROMIUM ALLOYS.

Certain services, such as the bearing surfaces of steam valve seats and discs, require a material which combines red hardness with corrosion and erosion resistance. An alloy of approximately 55 per cent cobalt, 30 per cent chromium, and 5 per cent tungsten is suitable for these services. This material maintains its hardness at 1000 degrees F. and decreases in hardness only moderately at 1500 degrees F. It is used in the form of a surface deposit. The method of application is by soldering or brazing with an oxy-acetylene torch, care being taken not to dilute the cobalt chromium alloy by melting the base metal.

* Assembled from data of A. S. T. M. and Babcock and Wilcox Tube Company Bulletin No. 6-B, 1936.

MATERIALS FOR SPECIFIC APPLICATIONS.

In selecting a material for a specific application, it is well to have in mind the relative importance of the various conditions of service. Thus, an optimum material may be chosen.

However, the interrelations between conditions of service and properties of materials are not always obvious. For instance, excessive creep will disarrange turbine clearances. But creep is a long time phenomenon. And the turbine may operate only a small fraction of its life under full load and maximum temperature.

Therefore, it appears desirable to discuss briefly some of the conditions of service which are inherent to specific applications.

TUBING FOR PIPES.

Pipes are subject to (1) hoop stress, and (2) stresses induced by expansion at high temperature. For shipboard installation the weight of pipes is a large proportion of the total machinery weight. Thus, high tensile strength to permit thin sections is the first requisite.

Tubing should be capable of manufacture into pipes without excessive heat treatment. Ductility should be provided for bending and, in some cases, cold rolling.

When tubing is welded to flanges, or where pipe is built up of sections of tubing welded together, the material should have good weldability, especially if the welding is to be done during installation in locations which lack ready accessibility.

Pipes must resist scaling in air and in steam at the maximum operating temperature.

Creep strength is not normally a prime consideration.

PIPE FLANGES.

The maintenance of accurate flange faces is important. Therefore, the flange should be stiff to resist bending and dishing from the heavy pull of the flange bolts. Thus, a high proof strength is demanded.

Good weldability should be provided when the flanges are to be welded to the tubing. It is the opinion of the writer that welded flanges will become standard with the introduction of higher pressures and temperatures.

Expansion coefficients should be closely related between the flange, the tube, and the flange bolts.

The operating temperature of flanges is somewhat less than that of the tubing. Thus, creep strength and resistance to scaling in air are of relatively low importance.

FLANGE BOLTS.

High tensile strength and high proof strength are of first importance.

Bolts should possess machinability consistent with strength requirements. They should resist galling and scaling in air so that the nut will not freeze.

Creep is of importance, although flange bolts operate at a lower temperature than either the flange or the tube. In operation the bolt will elongate under excessive creep stress and thereby relieve itself automatically.

VALVES AND FITTINGS.

Valves in particular should possess rigidity in order to maintain alignment between their various working parts. This requires high proof strength in the material. Nevertheless the designer should not count too much on the properties of the material, but should endeavor to improve the symmetry of his stress distribution. "Stream line" or "straight flow" valves with the stems set at an oblique angle are not consistent with symmetrical distribution of forces.

A low coefficient of expansion is desirable to maintain the alignment of working parts and thus prevent valves from freezing closed or leaking as the result of temperature changes. For the same reason, valve discs and stems should have a coefficient of expansion close to that of the body.

Weldability should be considered where joints are to be made by welding. Scale resistance is important, particularly in the working parts of valves.

The use of removable seats is of doubtful value in high temperature applications. This is attributable to the difficulty of maintaining a tight joint between the valve body and the removable seat.

The use of materials in combination for valve trim, and the properties of chromium cobalt facing for valve seats and discs, have been discussed previously.

BOILER SUPERHEATER DRUMS AND HEADERS.

Unlike pipe, boiler superheater drums and headers are not subjected to stresses from expansion. Hence, wall thickness is important only as regards weight and manufacturing difficulties. In small diameter headers, the thickness is usually controlled by the depth of the tube rolling surface.

Preheat for welding would be impracticable in a large diameter drum. However, a small header can be preheated. These criteria may affect boiler design for higher temperatures.

The material used should have good machinability for drilling and reaming tube holes. It should resist scaling in steam.

Since dimensional stability is not important, creep strength is secondary.

BOILER SUPERHEATER TUBES.

Superheater tubes are subjected to higher temperature than any other material under steam pressure in a steam plant. Therefore, strength properties, including creep strength, bear consideration. Also of prime importance is resistance to scaling in steam and in furnace gases.

For rolled joints in drums and in headers, and for cold bending to templet contour, ductility is required. The expansion coefficient should be close to that of the drum or header in order to maintain the integrity of the rolled joint.

The welding together of tube sections by resistance welding has been accomplished successfully in practice. The welding on of a tube end of different material from the tube proper, in order to provide good rolling qualities and a desirable coefficient of expansion, has been discussed above. Inspection of resistance welds is difficult. Process inspection and magnetic inspection provide the most satisfactory methods used at this time.

The welding of tubes into headers has been accomplished in practice.

TURBINE CASINGS.

Creep in turbine casings is important in the maintenance of clearances. High proof stress to provide rigidity is also a consideration.

However, unless present manufacturing practices, particularly for large turbines, are changed, the thick sections necessary to provide good castings also provide valuable strength characteristics. It is considered more justifiable to use extra weight in a turbine than in a pipe.

Castability is important to produce complicated sections. Weldability is also necessary for the repair of defects and for the welding on of flanges, spuds, and connections. Machinability has importance. These qualities are somewhat inconsistent with high unit strength. Therefore, increased sections are indicated.

Turbine casings must be fully annealed. They should resist scaling in steam.

TURBINE ROTORS.

Turbine rotors, like turbine casings, should be free of excessive creep and should be rigid. They also should have a coefficient of expansion close to that of the casting in order to maintain clearances.

The forging should be made from a carefully selected billet so that it will be free of internal defects and cracks. It should be free of internal stresses. It should resist scaling in steam.

In practice, it has been found that hardness is not essential to prevent distortion during the insertion of blades.

TURBINE BLADES.

To absorb shocks, as by water from a priming boiler, and to permit the riveting of tenons, turbine blades should be ductile. In some designs they should be weldable, to permit welded shrouding. They should possess high tensile strength to resist the stress set up by rotative forces. They should resist erosion and corrosion in order to maintain their flow contours.

Given proper design characteristics which prevent vibration, turbine blades need not have especially high fatigue resistance.

Cold or hot rolled blades are preferable to forged blades.

TURBINE NOZZLES.

The manufacture of turbine nozzles may be by various combinations or assemblies which involve welding, casting and machining. Machined plates may be cast or welded into a nozzle block.

The materials should be suitable to the various methods of assembly. The flow areas should present a smooth surface and be resistant to erosion and corrosion.

CONCLUSION.

The information compiled in this article has been obtained from several sources, but particularly from conversation and discussion with the many kind friends with whom it has been the writer's pleasure to be associated during his tour of duty in the Navy Department. In setting these thoughts on paper the writer has become more distinctly aware of the gap which is likely to exist between the materials engineer and the design engineer. Perhaps we need a third kind of engineer, a correlation engineer, who will devote his time to gathering and analyzing the latest information about materials. He would be a sort of journeyman to be called in when there was work for him to do. In any case, the writer's opinions are his own, and sincere, but subject to disagreement. It is hoped that from time to time, as new information is developed, others will continue where he has left off.

ACKNOWLEDGEMENTS.

The writer wishes to thank Mr. William C. Stewart of the U. S. Naval Engineering Experiment Station, for his work in obtaining data for the tables herein, as well as for his many valuable notes concerning the physical characteristics of various materials.

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METAL SPRAYING: FUNDAMENTALS AND APPLICATIONS.

By LIEUTENANT R. L. DENNISON, U. S. NAVY, MEMBER.

A great deal of mystery surrounds the use of molten metal spray guns in the minds of most engineers. While they realize that in spite of light density, considerable porosity, and a questionably sure adherence to parent metal that it must have a positive and useful field of proper employment, no one has charted the limitations clearly enough as yet to give sprayed metal the popularity which it will ultimately attain. When it has been properly and carefully applied it will sometimes give remarkable results as a protective coating—but not always. It has been used with conspicuous success to build back a damaged or badly scored shaft thus saving a heavy replacement cost—but such a repair is quite likely to result in an early failure, so where do we stand? The author believes that sprayed metal is not like cast metal, nor is it like weld metal, and should not be considered as possessing the properties of either. It can best be described perhaps as a mechanical atomic assembly, and as such is unique in the metallurgical field and possesses a set of characteristics all its own.

INTRODUCTION.

Metal spraying, as treated in this paper, is defined as the art of applying a coating of atomized metal to a surface. All methods considered employ air, nitrogen, or some other inert gas as an impelling medium for the atomized metal. A distinctive feature of the process is that although the metal is molten before atomization the temperature of the surface coated is raised but slightly so that paper, fabric, or other relatively inflammable surfaces may be coated in a manner similar to the coating of a metal base.

Four methods of applying a coating of metal spray are in use with varying degrees of success. In one method, molten metal

from a form of crucible is introduced into an atomizing blast of gas. In another, the metal to be sprayed is used as two electrodes and the blast directed across the gap. However, the only two spraying processes of commercial significance today are: first, blasting metal in the form of wire which has been made molten in an oxy-gas flame; and second, a somewhat similar process utilizing metal in a powdered form. The mechanisms involved in these processes are to be described.

In the early days of metal spraying extravagant claims were made. These claims were based more on wishful thinking than on research and experience. The principles and fundamentals of metal spraying were not then, and to a somewhat lesser extent, are not now fully understood. The process was highly exploited so that results did not meet expectations, with a consequent discrediting of the process. Much confusion has resulted in a comparison of metal spraying with welding. These processes are, of course, dissimilar except for the fact that metal may be deposited by both methods.

The principal applications of metal spraying are:

1. To build up machine parts.
2. To develop metallic coating protective against corrosion.
3. For decorative purposes.

There are other less important or less well developed applications.

There is much disagreement to be found in the literature applying to metal spraying. This is because of the complexity of the problem, and also because of the lack of standard control of the many variables. It is thought that a proper approach to the understanding of the problems involved in metal spraying and in its applications is a study of the nature of the sprayed coating. To this end the author will attempt a critical appraisal of the current views of the subject. In addition a brief history of the development of the metal spraying processes and explanations of typical applications will be given. Since, as has been previously stated, only two methods of spraying are at present of any commercial significance, this paper will be concerned mainly with metal sprayed from wire and powdered forms.

EARLY HISTORY.

The modern method of coating surfaces by atomized metal was developed mainly by the work of a Swiss engineer, M. U. Schoop. Schoop observed that lead bullets fired from a small-calibered rifle adhered to a target. This observation induced him to begin experiments in the coating of surfaces with metallic particles. Other investigators have also worked on the problem. Although the early development of metal spraying apparatus was made in Europe, there are records of early U. S. patents, applying to metallic spraying. In 1894 Edison was granted a patent (U. S. Patent 526,147) on a method of vaporizing material used as electrodes in an electric arc and depositing this material on an object placed near the electrodes in a vacuum chamber. In 1902 Thurston was granted a patent (U. S. Patent 706,701) for producing a metal coating using metal in the form of a powder driven by a blast of gas against a metallic surface. No provision was made for heating the particles of the coated metal. Experiments have shown that this method fails to produce adherent coatings.

In 1914 Morf, a Swiss engineer, obtained a patent on a device (U. S. Patent 1,100,602) which is quite similar to the wire spraying pistol in use today. He provided for means of feeding a wire through an oxy-gas flame at the orifice of a nozzle and of projecting the molten metal by means of compressed air. In 1915 Schoop obtained a patent (U. S. Patent 1,128,058) on an apparatus for spraying molten metal by means of an atomized air blast. This device was not portable. In another patent in 1915 (U. S. Patent 1,128,059) Schoop provided a method of plating with metal powder. This patent covered the method rather than any specific device for accomplishing his purpose. Also in this year Morf obtained a patent (U. S. Patent 1,128,175) on a method of melting and atomizing substances in order to produce sprayed coatings. Schoop also received in 1915 two patents (U. S. Patents 1,133,507 and 1,133,508) relating to spraying atomized metal produced when the metal to be sprayed formed the electrodes of an electric arc.

In 1917 Stolle, a German engineer, obtained a patent (U. S. Patent 1,221,104) on a device for spraying metal previously made molten in a form of crucible. In 1918 Stolle received another patent (U. S. Patent 1,262,134) relating to spraying of molten metal.

In 1923 Meurer, of Germany, obtained a patent (U. S. Patent 1,511,977) on a device for increasing the number of wires that might be sprayed from a nozzle. In 1925 Saeger obtained a patent (U. S. Patent 1,721,092) on an electrical device for spraying metals.

The commercial use of sprayed metal processes began abroad much earlier than here. It was not until the basic patents of the wire spraying devices expired that wide-spread use of this equipment began in this country. Many of the very early devices for spraying metal lacked the feature of portability. The early inventors also had many ideas concerning the nature of sprayed metal which are now known to be mistaken.

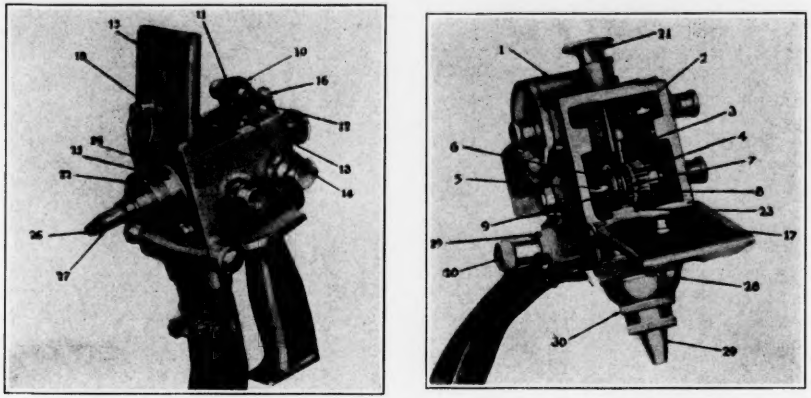
Among the powder pistols the " Schori " has been more successful than other designs. It is understood patent applications applying to this pistol are now being filed in this country. The molten metal pistol and the electric pistol are not in general use in this country today.

DESCRIPTION OF SPRAY PISTOLS.

Wire Pistol.

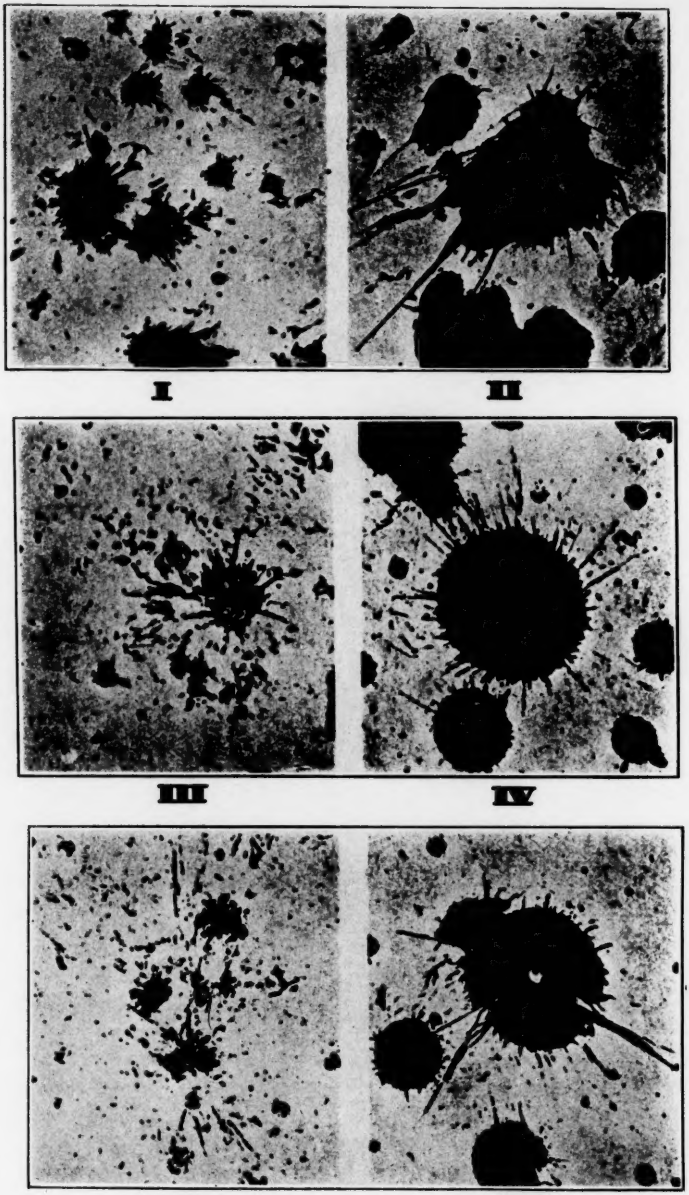
The wire-fed pistol is a device which will feed wire into an oxy-gas flame and atomize and project the molten metal by means of gas blast, usually compressed air. The nozzle in its simplest form consists of three concentric tubes. The inner tube contains the wire which is fed into the flame by a small air turbine contained in the pistol. The next annular tube carries the oxy-gas mixture which burns outside the pistol. The outer tube supplies the gas blast which atomizes and impels the molten metal. Wire pistols differ in detail, the principal difference being in the nozzle. Pistols built in England, France and America differ in this respect. In this country oxygen and acetylene are almost exclusively used as the combustible gases, although hydrogen, coal gas, or other hydrocarbon gases may be used in place of acetylene. Compressed air is likewise mostly used as the impelling gas. A typical American wire pistol is shown in Figure I.

The wire feed mechanism consists of those parts enclosed in the small aluminum box-like case (1). At the rear end of the case and lying crosswise is the turbine shaft (2) on which is mounted



Courtesy of the Metallizing Co. of America.

FIGURE 1.—WIRE SPRAY PISTOL.



From: "Metal Spraying," Charles Griffin & Co., Ltd., London, page 85.

FIGURE 2.—METAL PARTICLES SPRAYED ON GLASS × 50.

I.—Aluminum Sprayed on to Cold Glass.
II.—Aluminum Sprayed on to Glass Heated to 400 Degrees C.
III.—Copper Sprayed on to Cold Glass.
IV.—Copper Sprayed on to Glass Heated to 400 Degrees C.
V.—Nickel Sprayed on to Cold Glass.
VI.—Nickel Sprayed on to Glass Heated to 400 Degrees C.

the turbine impeller (not shown). This impeller is enclosed in the circular housing which is a part of the case, and it is the air jet striking the blades of the impeller which furnishes the power to move the wire feed mechanism. The turbine shaft is mounted on small annular bearings. Integral with the turbine shaft is a worm which meshes with a worm gear lying directly under the worm.

This worm gear is fastened to the counter shaft (3), which lies in a fore and aft position, and integral with this shaft is a worm which engages a gear (4), which is mounted on the wire feed shaft (5).

Attached to the worm gear by means of three small screws (6) is first the idler shaft drive gear (7), the knurled roll flanges (8), and the knurled (wire) feed roll (9).

Swung back out of the way is the idler shaft gear (10), and the idler shaft knurled roll (11), mounted on a bronze bushing (not shown), which runs on a shaft (12), supported by the idler shaft yoke (13).

This yoke swings on the trunion (14) which is adjustable for lateral position.

The cover of the gear case (15) is hinged at the front end and is held shut when the gun is in operation by the spring (16).

Mounted in the cover and directly over the yoke is the pressure plunger (17), which supplies the necessary pressure to the yoke to enable the knurled roll to engage the wire properly. This plunger is actuated by a spring (not shown) and is enclosed in a housing (18), which is adjustable so different pressures may be applied to the wire.

Underneath the front end of the case is a taper valve (19), which controls the gases and air. At the large end of this valve is an adjustment screw (20), which controls the speed of the turbine and resulting speed of the wire passing through the gun.

At the rear end of the case is the wire guide tube (21).

Underneath the case is a suitable grip for holding the gun while in operation.

The gas head consists of those parts which have to do with the metering and mixing of the gases and atomizing of the molten metal.

The main body (22) is attached to the wire case by the nut (23). Between the case and the main body are the orifice meter plates, the rear being (24) and the front (25). A predetermined amount of gas and oxygen is allowed to pass through these plates and is mixed in them as it passes through. It then passes on to the main body and is distributed.

The wire nozzle (26) is screwed into the main body and outside of the wire nozzle is attached to the main body, the gas cap (27).

Screwed to the main body is the air cap body (28), and attached to this at the front end is the atomizing cap (29) and the lock ring (30).

The amount of metal a wire pistol will deposit in given time is determined largely by the design of the particular pistol under consideration. Some pistols are designed to handle ⅛ inch rods, others use from 10 to 15 B and S gauge wire. Representative maximum figures for the wire type of pistol are approximately as follows: Zinc 25, aluminum 5, steel 7 pounds per hour. The gas consumption on an average maximum will be approximately 50 cubic feet per hour for oxygen and acetylene. Compressed air must be supplied at about 45 cubic feet per minute maximum. The pressure required is between 30 and 100 pounds per square inch.

The pistol is held from 4 to 7 inches from the work in coating metal surfaces. There will be a loss of 10 per cent or more of the metal sprayed when coating flat plates. This loss will be greater when coating other surfaces.

Powder Pistol.

The powder pistol is of simpler construction than the wire pistol since it does not contain any moving parts. The compressed air (or other inert gas) blast removes the powder from a chamber, which is separate from the pistol, by aspirating action and blows it through a nozzle at which the oxy-gas flame is situated. Because of the relative difficulty in handling powder this pistol will normally consume more compressed air than the wire type of gun. There is also said to be a greater loss in metal sprayed. It is claimed for the powder pistol that it will spray more metal per unit of time than the wire pistol.

Because of the difficulty of obtaining some metals in powdered form, the powder pistol has been used mainly for spraying of low melting point metals.

STRUCTURE OF METAL-SPRAYED COATINGS.

Schoop's original conception was that the formation of a cohesive and adhesive metal spray coating was fundamentally due to the transformation of the kinetic energy of the particles upon impact into sufficient heat to cause fusion. Arnold (E) has demonstrated mathematically that the theory is untenable and shows that in order to cause fusion the velocities of various metal particles in meters per second are as follows:

Lead	*Tin*	*Zinc*	*Aluminum*	*Copper*
337	446	763	1274	1046

Since the velocity of gas from a simple nozzle is little greater than the velocity of sound these velocities are not attained. By experiment Arnold shows the mean velocities of brass and zinc particles to be 120 and 140 meters per second, respectively. The calculations for velocity involve an assumption of particle temperature at the moment of impact, which Arnold takes as 70 degrees C. This value was stated by Schoop. It is a known fact that inflammable material may be coated by the metal spray and that even the hand may be coated without discomfort when held about 10 inches from the nozzle. However, the measurement of particle temperature is an exceedingly difficult problem and it is doubtful that the true temperature is as low as 70 degrees C. According to Schoop's theory cold metal particles could be sprayed, but this has not been successfully accomplished.

Other investigators, notably Turner and Ballard (M), [The letters following the names of authors refer to references listed in the selected bibliography at the end of this article], Turner and Budgen (O), and Rollason (P), favor the hypothesis that the molten metal particles from the flame cool slowly in transit because of little relative movement between them and the propelling blast and that also little heat is lost because of the short time interval. Arnold (E), Turner and Budgen (O), and Rollason (P), have shown "shadowgraphs" of various metals sprayed on glass (Figure 2). A pronounced splashing effect is to be noted. The ability

to coat inflammable material is explained by the low heat content of the individual particles and by the cooling effect of the air blast when the particles impact upon the surface.

It seems not unlikely that the sudden quenching effect of the cold air blast when the particles are drawn from the flame would create a thin solid envelope around each particle so that the central mass would remain molten during transit.

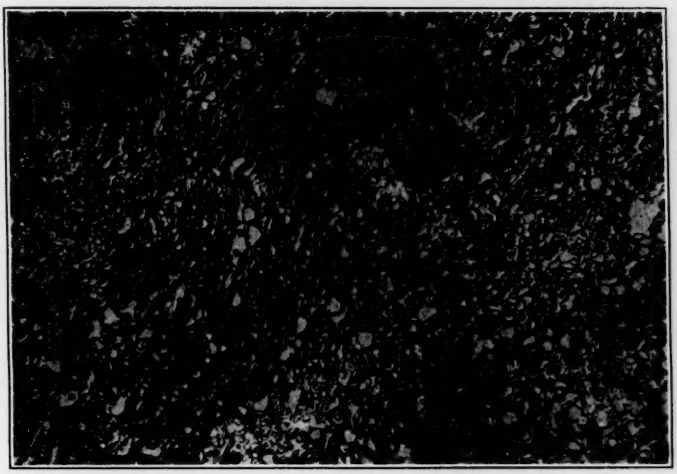
Rollason (P) has also shown by means of shadowgraphs an important difference between deposits of high melting point metals produced by wire and powder processes. The powder process does not give the splash effect to such an extent as the wire process. This may explain why the powder process does not appear to give as good a bond as the wire process and therefore has not been as successful in applications such as building up machine parts.

Regardless of the kind of metal deposited, all sprayed coatings show a laminar or stratified microstructure when viewed in a plane parallel to the spray axis. This is shown in Figure 3 which is sprayed brass. The surface normal to the spray axis shows a round flaked effect with the flakes irregularly superposed. Typical surface views are shown in Figures 4, 5, and 6.

The deposit is thus seen to be constituted of layers of interlocking saucer-shaped plates. The laminar structure is generally thought to be due to an oxidation effect. In general all investigators agree that there is no alloying of the deposited metal with the metal base. It may be stated that the bond between the coating and the base metal and between the particles of the coating themselves is largely, if not entirely, mechanical. With this understanding of the structure of sprayed metal coating many of its limitations will become evident.

Since the inclusion of oxides affects the homogeneity of the structure, it is desirable to reduce the oxidation of sprayed metal. Sillifant (D) believes that oxidation may occur in four distinct phases. Namely; one, in the flame zone, if this contains excess oxygen; two, when the molten metal is removed from the tip of the wire by the air blast; three, on the surface on the sprayed article by exposure of metal particles to the air blast and to the atmosphere; and four, if the sprayed article becomes excessively heated. He does not include the possibility of oxidation occurring through

FIGURE 3.—SPRAYED BRASS (65 PER CENT CU.-35 PER CENT ZN.) × 100.
Section Parallel to Spray Axis. Etched in Acidulated Ferric Chloride.



U. S. Naval Engineering Experiment Station.

FIGURE 4.—SPRAYED ASCOLOY (18 PER CENT CR.-8 PER CENT NI.) × 100.
Surface Normal to Spray Axis Etched in Acidulated Ferric Chloride.

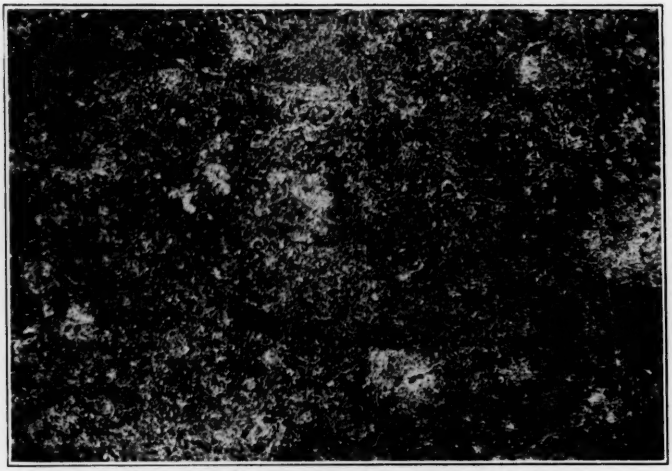


FIGURE 5.—SPRAYED ZINC × 100.
Surface Normal to Spray Axis Etched in Acidulated Ferric Chloride.

U. S. Naval Engineering Experiment Station.

FIGURE 6.—SPRAYED HIGH CARBON STEEL × 100.
Surface Normal to Spray Axis. Etched in 5 Per Cent Picric Acid in Alcohol.

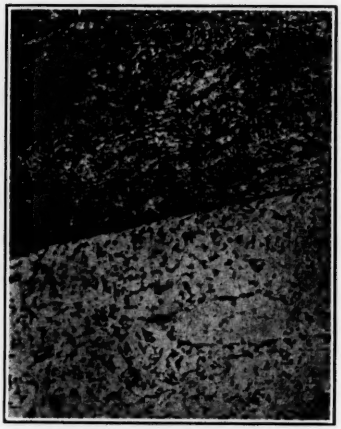
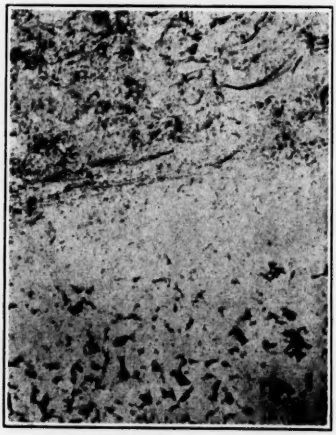


FIGURE 7.—0.09 PER CENT CARBON STEEL SPRAYED WITH DISSOLVED ACETYLENE USING NITROGEN AS IMPELLING MEDIUM. ETCHED × 100.



"Engineering"—5 Nov., 37.

FIGURE 8.—SAME AS FIGURE 7, BUT AFTER HEAT TREATMENT AT 900 DEGREES FOR 1 HOUR. ETCHED × 100.

dissociation of water vapor in the oxy-gas flame. This possibility was noted by Arnold (E). Rollason (P) has pointed out that oxidation may be lessened if a reducing flame is used, and if the pistol is held close to the work. He further states that neither of these suggestions is practicable. Sillifant (D) has investigated the spraying of 0.9 per cent carbon steel on a bar of 0.30 per cent carbon steel, substituting nitrogen for air as the impelling medium. Upon photomicrographic evidence, he reports an improvement in the structure of the sprayed coating using nitrogen and ascribes this to a reduction in oxidation. No analysis of the sprayed metal for oxides are given. He also shows that after heat treatment at 900 degrees C. for one hour there was a migration of carbon from the core to the coating and, further, that the coating had begun to resolve into a definite crystalline structure. Figures 7 and 8 illustrate these results. After two hours heat treatment at 900 degrees C., the individual particles of the deposit had split up into grains. In order to show the improvement in the coating produced by this process, he made a 90-degree bend test on a bar 9 inches long and ¾ inch diameter. The bar was bent cold and showed no dislodging or fracturing of the deposit. Unfortunately he showed no comparative tests made with a deposit using air as the impelling medium.

Ballard (G) believes that little or no oxidation takes place during spraying but that each particle is oxidized after deposition. Copper has been used by some investigators in studying the control of oxidation mainly because of the relative ease with which the analysis for oxides may be made. Ballard and Harris (B) in investigating oxidation of sprayed copper coatings conclude that the substitution of nitrogen for air does not give appreciable effect in reducing the amount of oxides formed. They state that the powder system of spraying gives more oxidation than the wire system. There has thus far been no general agreement that an improvement in the amount of oxide in a sprayed deposit may be obtained by using nitrogen in place of air. It may be mentioned that the cost of using nitrogen would quite likely offset any gain effected by possible betterment of the coating. It is now believed that preheating the surface tends to encourage the formation of an oxide film, and hence the preheating practice as recommended by Turner and Budgen (O) is not now generally followed.

PHYSICAL PROPERTIES OF SPRAYED METAL.

In assaying physical characteristics of sprayed metal it should be remembered that the quantitative values obtained depend not only on the method of spraying employed but on the technique. The metal coating, as will be seen by studying the structure, will also show directional characteristics. These considerations make it difficult if not impossible to accept any fixed values for various properties such as hardness, tensile strength, or density. It is also difficult to reconcile results reported by various investigators. With these limitations in view, a brief review of the physical properties of sprayed metal will be given.

Hardness.

As has been shown, sprayed metal is somewhat similar to cast metal, if not in the aggregate, at least in individual particles. The nature of a sprayed metal coat is somewhat different from a cast metal coat in that the sprayed metal will, in general, show a higher percentage of oxide, more porosity, and will have a laminar structure.

Although in an early work Arnold (E) has shown that the hardness of sprayed metals measured by the scratch hardness method may be as much as 35 to 40 per cent less than the same metals in the cast form, Turner and Ballard (M) report that the hardness of sprayed metal is greater than the corresponding cast metal by the scratch and scleroscope methods and little difference shown by the ball indentation test. Ballard (G) states that X-ray analysis shows that the particles of the sprayed metal are slightly work-hardened and that combined with an oxide film sprayed metal gives a total hardness slightly in excess of metal in the cast state.

Fassbinder and Soulary (A) state that when nitrogen is used instead of compressed air as an impelling medium, the hardness of sprayed high melting point metals such as mild steel and 18-8 stainless steel is reduced, and that the hardness of low melting point metals such as aluminum and tin is but little affected. They have also measured the hardness on the inner surface and outer surface of sprayed shells and find that inner hardness may vary from outside hardness by as much as 20 per cent in 18-8 sprayed coating and from 3-5 per cent in aluminum and zinc coatings, the inner surface being harder.

Tensile Strength.

Mathy (J) has reported tensile tests of sprayed metal made at the California Institute of Technology. The method used was to spray a thick coating on a surface, strip the coating by chemical means and then place the resulting specimens of pure sprayed metal in an appropriate tensile machine. The results are shown in Table 1.

TABLE 1.

Properties of Sprayed Coatings

Sprayed Coating			Pure metal, cast, and annealed		
Elongation in 2 in.	Ultimate Strength	Specific Gravity	Metal	Elongation in 2 in.	Ultimate Strength	Specific Gravity
1.3%	4600	6.46	Zinc	65%	16000	7.14
1.1	4900	2.44	Aluminum	45	13000	2.71
nil	4400	7.91	Copper	58	32000	8.94
1.3	3300	6.95	Tin	80	3000	7.30
1.5	1950	---	Lead	64	2000	11.34
nil	3750	---	66-34 Brass	60	45000	8.47

From: "Metal Progress," 29 April, 1936, page 56.

It should be noted, as might be expected, that the ductility is relatively very low and that the metals show in general that sprayed metal should not be used in applications where tensile strength is an important factor.

Density.

As might be predicted, the densities of sprayed metals are found to be lower than the corresponding metal in the cast form.

Typical density measurements are given in Table 2. The densities reported were measured by pyknometer method.

Table 2.-Density of Sprayed Metals as Compared with the Density of the Metals in Ordinary Form.

Metal	Turner and Ballard	Arnold	International Critical Tables 1926
			Grams per cubic centimeter, at 20 C.
Aluminum.....	2.4	2.31	2.70
Zinc.....	6.4	6.32	7.14
Tin.....	7.1	6.82	7.31
Iron.....	6.5	...	7.86
Copper.....	8.0	7.51	8.92
Lead.....	...	9.77	11.34

From: Rawdon, "Protective Metallic Coatings," page 49, Chemical Catalog Co.

Adhesion of Coating.

Tests have been made at the U. S. Naval Engineering Experiment Station on metal sprayed static torsion test specimens. In these tests German silver, aluminum, commercial bronze, cadmium, copper, and zinc were sprayed individually by means of a wire-fed pistol on the test lengths of six steel static torsion test specimens. The specimens after being subjected to test showed that the German silver and aluminum coatings started to flake off at a stress only slightly below the yield point of the steel. The commercial bronze and copper coatings started to peel off at the yield point, while the cadmium and zinc coatings began to come off at an angle

of twist of about 150 degrees, or about 75 degrees above the angle of twist at the yield point. Practically the same maximum torsional strength was obtained for uncoated and coated specimens. It was also shown that sprayed coatings of the metals mentioned above do not flake off when the base material is subjected to stress in a rotating bend fatigue test.

Fassbinder and Soulary (A) report as a result of tensile tests that zinc coating on a mild steel base did not exhibit cracks until the stress in the base metal was of the order of the elastic limit.

These tests show that very good adhesion of sprayed metal coatings on steel may be expected under static and dynamic load condition. The more ductile metals seem to give greater resistance to flaking or peeling.

Porosity.

From an examination of the micro-structure of sprayed metal it is evident that porosity to a varying degree is a characteristic of all sprayed metal. The solidity of sprayed layers of low melting point metals will in general be greater than that of the higher melting point metals. Porosity may be overcome to some extent by spraying some low melting point metal such as lead or tin as a layer in a metal coating of some higher melting point metal. Subsequent heating above the melting point of the low melting point metal will cause it to fill pores in the sprayed coating. Buffing, or polishing of the surface will accomplish the same result on the surface of a soft metal. The matte finish which is characteristic of sprayed metal coats provides an excellent holding surface for varnishes or paints. These, also, may be employed in a suitable environment to make an impervious coating.

Reininger (F) has conducted experiments with sprayed coatings on a brass base. Nickel was selected because of its definitely coarse structure when sprayed. The sprayed specimens were coated with thin copal and thin bakelite varnishes. These varnishes permeated the interstices of the sprayed metal. It was shown that the test pieces, having varnish coatings, might be deformed plastically to a higher degree than those with ordinary coatings. It is stated that resistance to chemical action was greater because of the impervious sprayed coating produced by the use of these var-

nishes. It was also stated that the corrosion resistance was definitely improved.

Shaw (Q) has conducted experiments in a friction machine on journals of hardened and ground steel shafts in comparison with shafts having a sprayed steel coating. It was found that the coefficient of friction was considerably less in the case of the sprayed steel shafts. It was also found that the sprayed steel shaft seized at loads about 4 times the load required to seize the plain steel shafts. Another series of tests were run with lubricating oil supply cut off. It was found that the hardened steel shafts seized after about 3 hours while sprayed steel shafts ran for 22½ hours. These results are attributed to the fact that the porous sprayed coating tends to maintain a reservoir of oil which aids in keeping intact the lubricating oil film. It is further reported that specimens of sprayed metal submerged in oil for 50 hours were found to have absorbed 10 per cent by bulk of oil.

PREPARATION OF SURFACE.

Since the bond between the sprayed coating and the base metal is largely, if not entirely, mechanical, the preparation of the surface to be coated is without doubt the most important factor in the successful application of a sprayed coating, particularly when thermal or mechanical stresses are to be considered.

In preparing flat surfaces sand or grit blasting is universally used. The object is to obtain a roughened surface upon which the sprayed particles may interlock. Shot blasting, which merely peens the surface is of little or no value. Lake or sea sand are not recommended. A hard white quartz or angular flint sand or numbers 30 or 40 angular steel grit should be used. The use of steel grit means a high initial expense but it may be recovered and reused many times oftener than sand. It is also safer for the operator from a health standpoint.

In preparing journals and other machine parts having circular cross sections for spraying a common practice is to cut a dragging thread of from 16 to 24 per inch, depending on the diameter of the piece. In order to do this a sharp V-point tool is set so that the point is below the axis of the work as it turns toward the operator. This operation is accomplished after the work has been turned

down. An undercut is taken at the ends of the threaded section to provide anchorage.

This method of surface preparation is open to at least one serious criticism, particularly if the article is to be subjected in service to dynamic stressing. The undercutting and grooving provide localities of high stress concentration under dynamic load conditions. This feature should be carefully investigated in individual cases where it is proposed to build up cylindrical sections.

It has been shown by the U. S. Naval Engineering Experiment Station that the sprayed metal does not add fatigue resistance to notched specimens.

In doubtful cases a sufficiently good bond might be obtained by grit blasting as is done in the case of a flat surface and without the under-cutting.

SPRAYED METAL FOR CORROSION PROTECTION.

Metal spraying finds one of its most useful applications in applying coatings for protection against corrosion. The most significant advantage of this process over other methods is that the sprayed coat may be applied to larger structures *in situ*. This feature is of particular advantage in applying protective coatings to ship structures or to bridges. The process may be applied after welding or riveting and results in a protective coat over the entire surface. The discussion to follow will mainly be concerned with the protection of iron (steel) since this metal is most widely used for such purposes as require corrosion protection. In order more fully to explain the nature of the protection afforded by the sprayed coat, the theory of corrosion will first be briefly reviewed.

Theory of Corrosion.

It is well established that metals do not corrode in dry air. Corrosion usually necessitates the dissolving of the metal which will exist in the final corrosion product in a higher state of oxidation. A necessary and sufficient condition, therefore, to prevent corrosion, is to provide a coating which will be impervious to moisture. The protection thus given to the base metal will then depend upon the corrosion resistance of the coating. This condition is difficult to realize when using metal as a protective coating.

Metals differ decidedly in their tendency to dissolve in the presence of an electrolyte. This tendency to pass into the ionic state is measured by the "solution pressure" of the metal. When two dissimilar metals are placed in the presence of an electrolyte, the one having the greater solution pressure dissolves first and in so doing protects the other from corrosion attack. The solution pressure of a metal is not susceptible of direct measurement. The well known electromotive series of metals, however, lists the metals in order of electrode potentials and gives practically the same information as would a listing of metals in order of solution pressure.

Table 3. Electrode Potentials of Metals

Difference of potential at the interface between a metal and its solution of normal concentration in which it is immersed

METAL	ION	DIFFERENCE IN POTENTIAL Volt
Gold (approx)	Au^{+++}	+ 0.985
Platinum	Pt^{++}	+ 0.86(?)
Silver	Ag^{+}	+ 0.7987
Mercury	$(Hg^{+})_2$	+ 0.7928
Copper	Cu^{++}	+ 0.3469
Hydrogen	H^{+}	0.000
Lead	Pb^{++}	- 0.132
Tin	Sn^{++}	- 0.146
Nickel	Ni^{++}	- 0.20
Cobalt	Co^{++}	- 0.23
Iron	Fe^{++}	- 0.34
Cadmium	Cd^{++}	- 0.420
Chromium	Cr^{+++}	- 0.47
Zinc	Zn^{++}	- 0.770
Aluminum	Al^{+++}	- 1.337
Magnesium (approx)	Mg^{++}	- 1.8
Sodium	Na^{+}	- 2.715
Potassium	K^{+}	- 2.925

From: Rawdon, "Protective Metallic Coatings," page 18, Chemical Catalog Co.

Table 3 shows the numerical value of electric potential at the interface between any metal and a solution of the same metal in which it is immersed.

Although the values given in Table 3 are not strictly applicable except when metals are immersed in a solution of the same metal, their behavior when immersed in the same electrolyte is, in general, as would be indicated by their positions in the electromotive series.

That is, the more electronegative metal goes into solution first. Hence when iron and zinc, for example, are together in the presence of moisture, the zinc dissolves first and in so doing protects the iron. It should be noted that the protection is afforded by the sacrificial action of the zinc. There is lack of general agreement concerning the exact position of the metals in the electromotive series particularly in regard to the relative position of iron and cadmium and also tin and lead. Rawdon (R), however, shows that in a solution of sodium chloride cadmium is quite evidently protective to iron.

If the information given by the electromotive series could be literally interpreted to apply to corrosion protection of iron we should expect that all metals listed below iron, and hence electronegative to iron, would protect this metal by sacrificial action. This is not entirely realized in practice, however. Aluminum, for example, does not generally afford the protection its position in the series indicates. This is because in corroding, the aluminum itself is protected by a closely adhering film of oxide or hydroxide. For much the same reason chromium does not always protect as indicated.

Protection by Impervious Coat.

Environment has much to do with the selection of a protective metal coating. From the nature of sprayed metal it is seen that the establishment of an impervious coating is unlikely. Hence if metals such as nickel, tin, or copper are used as protective coatings these metals being electropositive to iron will in the presence of moisture hasten the corrosion of the iron. As mentioned above, Reininger was able to produce a relatively impervious coating by impregnating a nickel sprayed coat with thin varnish. This method would not be of value if the surface were exposed to organic solvents such as alcohol or ether. Peening or buffing the surface may result in a betterment of the porosity but in general the metals electropositive to iron should not be used for a corrosion protective coat for this metal.

Protection by Anodic Action.

It is in the coating of iron with metals electronegative to it that metal spraying has its greatest application in the field of corrosion

protection. Zinc is the metal commonly used not only on account of its efficiency in protection but also on account of its low cost. Little information is available concerning the relative protection afforded by a zinc coating applied by spraying in comparison with zinc applied by other methods such as galvanizing. It may be said, however, that by far the most important factor is the amount of zinc present regardless of how it is applied. If an impervious zinc coating could be applied it would obviously be superior to the same amount of zinc if the coating of the latter were porous. For this reason, corrosion action may be retarded by painting the zinc after application.

The U. S. Naval Engineering Experiment Station has tested steel specimens sprayed with aluminum, brass, commercial bronze, copper, nickel, ascoloy, and zinc in a hot normal salt spray (130 degrees F.). After 100 hours' exposure the coatings tested in order of resistance to corrosion were as follows:

1. Aluminum.
2. Zinc.
3. Nickel.
4. Brass.
5. Ascoloy.
6. Copper.
7. Commercial bronze.

The high position of aluminum may be due to the effect of the spray in washing off corrosion products which ordinarily might serve to make the aluminum inactive after corrosion had started.

After 2 months all specimens except those aluminum and zinc coated were damaged to such an extent that continuance of the test was not indicated. After 4½ months it appeared that the zinc was somewhat more protective than aluminum.

In a comparative test a 2-inch steel pipe was sprayed, one section with cadmium and one with zinc. The sample was rotated at 1000 R.P.M. in brackish river water at a mean temperature of 78 degrees F. for 21 days. On completion of test the cadmium sample showed slightly greater weight loss than the zinc. The cadmium also showed shallow pitting while the zinc loss was uniform. Both metals afforded adequate protection. Because of metal costs, the cadmium coat will be considerably more expensive than zinc.

Aluminizing.

It is sometimes necessary or desirable to protect iron from oxidation at high temperatures. The calorizing process is well known in this field. An inexpensive substitute for calorizing is found in the spraying of aluminum on the steel parts to be protected, followed by suitable heat treatment. This is known as aluminizing. The result is said to be a coating having less life than the calorized coat but affording satisfactory protection. On the other hand the spraying process is less expensive and can readily be applied to large structures. Ballard (G) reports structures 30 feet long and 9 feet in diameter having been aluminized.

In aluminizing the aluminum is sprayed on the object which is then covered with bitumen or some similar protective coating to prevent too rapid oxidation during heat treatment. The object is then heated somewhat above 659 degrees C., the melting point of aluminum. The aluminum then diffuses into the base metal. The process may also be adapted to sprayed aluminum on non-ferrous metals.

The principal protection afforded to the base metal against oxidation is by the tenacious coating of aluminum oxide formed on the surface. Since at temperatures above 970 degrees C. there is rapid diffusion of aluminum into the base metal, this represents about the temperature limit for protection of ordinary steel by this method.

Aluminizing finds useful application in coating superheater tubes, pyrometer tubes, furnace parts, and aircraft exhaust manifolds. When used on chain grates or grate bars it is said to prevent in a large measure the burning on of slags.

BUILDING UP MACHINE PARTS

Metal spraying is coming into increasing use as a method of building up worn machine parts, such as journals, pump plungers, pistons, and cylinder liners. As has been previously mentioned, the proper preparation of the surface is of the greatest importance in obtaining a satisfactory coating. After the surface has been properly prepared it is important that the piece to be sprayed as soon thereafter as possible in order to minimize the opportunity for

a thin oxide film to form on the surface of the work. The piece should not be handled, as even the moisture from the hands of the workman may affect the result. It should not be necessary to wipe the piece with ether or alcohol after spraying, although this may be done if there is any doubt that the surface is not clean. It is, of course, essential that dry air be used in the sand or grit blasting if this method of surface preparation is used.

Not nearly so high a degree of skill is required of the operator of a spray pistol as of a welder. The order of skill required is about the same as for the proper handling of a cutting torch. Any good mechanic should be able to learn to handle the spray pistol with little practice. In most machine work it is possible to mount the work in a lathe with the pistol mounted on the tool carrier. Common practice is for the work to revolve at a peripheral speed of about 20 feet per minute and the pistol to advance 0.010 inches for each revolution of the work. It has been claimed, but has not been shown, that it is advantageous in reducing the percentage of oxide in the coating to adjust the operation so that the coating may be completed in one traverse of the pistol along the axis of the work. If this method is adopted it is usually necessary to apply an air blast to the back side of the work to keep it cool.

All sprayed metal may be machined although there may be some difficulty in machining a sprayed deposit of high carbon steel. Wet grinding is sometimes used.

In building up such parts as journals or pump plungers it is usual to provide a sprayed coating thickness of about 1/32 inch per inch of diameter. In building up parts for a press fit it will probably be found best to prepare the shaft by blasting and to apply the minimum thickness of coating possible. The spraying process has been used successfully in the spraying of thin babbitt bearings. This application has, however, not been thoroughly investigated. In deciding to use the spraying process in repair work, good judgment must be used. The nature of the sprayed coating should be understood and carefully considered. Speaking generally the coating will approximate a cast metal more closely than a forged metal. It will be brittle and have little tensile strength. For this reason it is of greatest value when applied where the principal stress to which it will be subjected is compression.

CONCLUSION

Considering the wide-spread use of the metal spray process there is remarkably little information of true scientific value available. However, there has been an increase in research work on this subject in recent years. Metal spraying in the past has progressed principally by empiric method. The extrapolation of lessons learned by experience into fields of new applications is not a sound method of advance unless, as is not always the case, the conditions applying to the old and new applications are similar. It is believed that there is need for considerably more research into the fundamental nature of sprayed metallic coatings and into the effects of control of the many variables in the spraying problem.

Metal spraying doubtless has many important applications. The advantage of this process in applying a protective coating to large structures after fabrication has been mentioned. Also, for example, spraying is practically the only method by which a coating of pure aluminum can be obtained. The deposition of metal coating without unduly raising the temperature of the surface is an important factor in such applications as building up worn or scored journals on armature shafts.

Metal spraying will without doubt continue to be more and more widely used in its many fields of application as the advantages and limitations of the process become more generally understood.

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HIGH TEMPERATURE PROPERTIES FOR SOME ALLOYS OF PARTICULAR INTEREST TO THE NAVY.

By William C. Stewart, Member.*

The creep of metals, particularly at the higher temperatures, is a matter of increasing concern to structural engineers, who are now commencing to realize that this widely-varying property of metals in common use today may be of critical importance to them. As data on creep has slowly been assembled over the last fifteen years, it has become increasingly apparent that the phenomenon accounts for many of the hitherto mysterious failures which have occurred in all kinds of structures.

However, creep-testing apparatus, especially that suitable for measuring the property in metals at high temperatures, is expensive, delicate, and difficult to design. Also, creep tests to be of value must be run over long periods of time; the available apparatus is absorbed in the conduct of a limited number of tests, and, in consequence, the output of information is distressingly small. The data presented by Mr. Stewart in this article will, therefore, be of particular interest to students of the phenomenon who are busily filling the blank spaces in the field of existing knowledge, but it will also be interesting to many others who are not yet familiar with the strange vagaries to which many metals are subject by reason of it.

INTRODUCTION.

The purpose of this paper is to present some creep test data and related properties for several cast low-alloy steels and cast composition bronzes which are of particular interest to the Navy. Published creep test results for cast steels of this type are few and no similar data for the cast composition bronzes have been

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noted. This investigation was not undertaken as a general study of creep in metals but for the purpose of providing information that would be useful to the Navy for new construction.

The problems presented by the design of equipment for use at elevated temperatures are many, and during recent years developments in the chemical and oil refining industries and in power plants have created a demand for metals which will operate satisfactorily at temperatures as high as 1350 degrees F. and for special purposes at even higher temperatures.

Interest in the creep of metals at elevated temperatures dates back to about 1920. It was not until about 1926 that the attention of engineers was directed to the behavior of metals at elevated temperatures as affecting the life and reliability of certain types of engineering structures. Since that time, numerous investigations, considering one phase or other of the creep problem, have been undertaken and a considerable number of papers have appeared in the technical literature.

The subject of strength of materials has been developed to a large extent by civil engineers in connection with their work. Steel was known to possess excellent elastic properties at atmospheric temperatures. Moreover, good design permitted of only elastic deformation in a structure. The realization that steels and other metals exhibit an essentially different character at elevated temperatures than at atmospheric temperatures resulted in attention being given to the testing of metals at high temperatures. Naturally, the knowledge that metals exhibit flow characteristics at elevated temperatures caused much concern among those responsible for the safety of plants using high temperature equipment. This circumstance aided materially in advancing investigative work and in directing the attention of investigators to the importance of the problem.

At first, tests at elevated temperatures were made for the purpose of determining, what are termed, short-time tensile properties. This was an attempt to duplicate the ordinary tensile test under conditions of elevated temperatures. It was soon recognized that tensile tests at elevated temperatures presented difficulties, either not encountered or present to a much less degree, in similar procedures at ordinary temperatures. Moreover, it was found that

the difficulties in testing increased as the temperature of the specimen under test was increased. While the short-time tensile test provides useful information, these values furnish no reliable index as to the creep characteristics of the metal.

Creep testing apparatus had to be designed and constructed by plants and laboratories undertaking investigations since no equipment was available on the market. A study had to be made of furnaces, in regard to size, method of winding, insulation and heat distribution. Some type of loading mechanism had to be designed and constructed. The construction of this part of the apparatus required particularly careful attention in order to insure proper and concentric loading of the specimen. More care had to be exercised in locating creep testing equipment than was necessary in the case of a tension machine. Experience has shown the necessity for a location free of drafts and vibration. Among the most important accessories of creep testing equipment are temperature controllers and recorders. Progress in the technique of creep testing has been made possible by improvements made in temperature control equipment. Finally, means had to be devised for measuring the elongation in the specimen as the test progressed.

In light of these facts, it is not surprising that creep testing installations showed considerable variation in design. Although an existing installation may have served as a pattern, most builders modified the design to meet their particular requirements. Today creep testing apparatus is being introduced which shows considerable departure from the conventional type. Such equipment has for its goal more accurate temperature distribution and control; an increase in the number of tests which it is claimed is made possible by the use of multiple units and even multiple specimens in the same straining system and, finally, greater sensitivity of creep measurement which is accomplished by the use of relatively long specimens.

It will be seen, therefore, that creep testing presented a formidable technical problem. Moreover, with the best of success a relatively long time would be required before any considerable number of test results were available. This type of program was not very encouraging to users of alloys for high temperature service. Hence, numerous attempts were made to develop some type of

short-time creep test which would provide creep information in a few hours instead of several hundred or a thousand hours. No attempt will be made to describe the various methods and procedures developed for this purpose. Although short-time creep testing methods appeared to have some value; in general, the results were disappointing in so far as eliminating the necessity for the long-time tests was concerned. The generally accepted opinion today is that reliable creep data can be obtained only as a result of the long-time creep test. Moreover, the present tendency is to conduct tests for longer rather than for shorter periods. The most satisfactory creep test would extend over a period corresponding to the expected life of the material in service. Obviously, this procedure would not be practicable; hence, investigators and others have attempted to extrapolate creep rates over periods equivalent to ten to one hundred times the actual time of the test. While this procedure appears to be fairly reliable for temperatures within the strain-hardening range of the material, discretion must be exercised in the use of this data. As test results for longer periods become available, extrapolation will become more dependable.

Considering the manner in which creep testing apparatus was developed and the difficulties in maintaining constant temperature conditions over long periods of time, it is not surprising that considerable lack of agreement exists between the results obtained by various laboratories. Until quite recently, this disagreement has been attributed mainly to differences in equipment, variations in temperature conditions and methods for determining elongation. Today it appears that many of the creep testing installations are of reasonably good design and that the technique is becoming standardized to a considerable extent. Notwithstanding this advancement, creep test results obtained by different laboratories for similar materials have shown discrepancies of considerable magnitude in some instances. Hence, it appears that creep behavior in metals may be conditioned by relatively slight differences in chemical composition, thermal history and deoxidation practice.

As a result of the work of the Joint High Temperature Committee of the A. S. T. M. and A. S. M. E., considerable progress has been made in the direction of standardizing creep testing apparatus, test specimens, temperature control and methods for pre-

senting creep data. Through this Committee, efforts have been made and are being made to compile and correlate creep data obtained from various cooperating laboratories. This Committee has also sponsored a number of projects for the investigation of special creep problems.

EQUIPMENT.

The long-time creep tests herein described were made using equipment as developed and installed at the Naval Engineering Experiment Station. Nine units each with a temperature controller and recorder are available. Eight of the units are assembled in a continuous framework, the other being an independent unit. For each unit, the load is applied to the specimen by means of standard weights acting through a lever mounted on knife-edge supports. The lever arrangement produces a ninefold multiplication of the dead weight applied. The apparatus is located in a well insulated room having two exhaust blowers for air circulation. The room is also provided with an automatic steam regulator for controlling the temperature during the winter months.

SPECIMENS.

Standard threaded end specimens 0.505 inch diameter, having gauge lengths of either 2 inches or 4 inches, are used. The longer specimen is used when available material permits since greater sensitivity is obtained with the longer gauge length. The 0.505 inch diameter is used whenever possible so as not to introduce errors resulting from different degrees of oxidation.

MEASUREMENT OF FLOW.

Extension in the test specimen under load and temperature is determined by means of the separation of platinum wires which are secured to the gauge points on the test length of the specimen. These wires are held rigidly in grooves .002 inch deep at the gauge points by means of knife-edge clamps of high speed steel. Two sets of wires each 180 degrees apart are used on each test specimen. Thus, the average extension for both sides of the specimen is obtained. The separation of the platinum wires, corresponding to the

elongation in the specimen between the gauge marks, is determined with a micrometer telescope assembly.

This instrument consists of two telescopes mounted on a micrometer slide. The lower telescope is fitted with a filar eyepiece; the upper telescope, with cross-hairs only. The use of platinum wires extending from each gauge mark makes it possible to determine changes in elongation by means of the single telescope containing the filar eyepiece. However, the use of both telescopes is convenient when a rapid rate of flow is being followed.

Some small natural spot occurring near the end of each platinum wire is selected as a reference point. A sketch is usually made of these spots for convenience of location in case the observer should forget the characteristics of the selected points. With experience this precaution is not necessary since the observer is able to locate the spots without difficulty. A natural spot on the platinum wire is preferred to a mechanical scratch, since the latter is considerably magnified by the telescope. For temperatures up to 1200 degrees F., no difficulty has been experienced with the natural spot being altered by the thermal conditions. Each test unit is provided with a rigid post for mounting the telescope, and readings are taken by moving the instrument from post to post. An electric light bulb attached to the barrel of the telescope throws light through a quartz window in the furnace side illuminating the ends of the platinum wires. With this assembly readings reproducible to 0.00005 inch in a 2-inch gauge length may be obtained.

CREEP RESULTS FOR SOME CAST LOW ALLOY STEELS.

Time-extension curves for specimens of cast carbon-molybdenum steel at 600 degrees, 700 degrees, 800 degrees, 850 degrees and 900 degrees F. temperatures are presented in Figure 1. The item numbers on the figure identify the several lots as to chemical composition and the original form of the material as shown in Table I. The numbers adjacent to the curves designate the stresses in pound per square inch. Results shown in Figure 1 were obtained with specimens having a test length of 4 inches. Similar time-extension curves obtained with 2-inch gauge specimens of all weld metal, Item 4 of Table I, are shown in the upper part of Figure 2. The

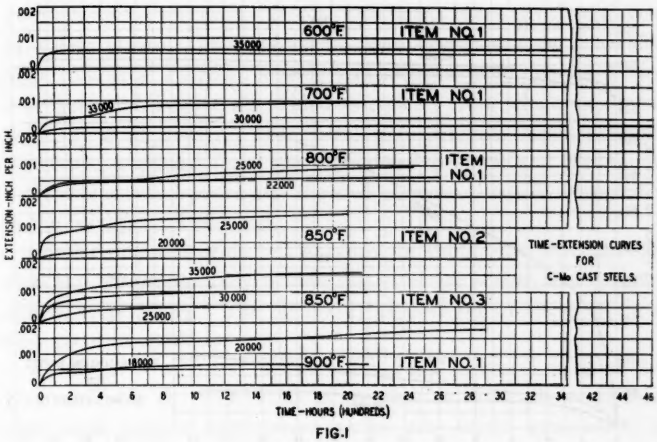

600°F.
ITEM NO.1
33000
700°F.
ITEM NO.1
33000
30000
800°F.
ITEM NO.1
25000
22000
850°F.
ITEM NO.2
25000
20000
35000
850°F.
ITEM NO.3
30000
25000
900°F.
ITEM NO.1
20000
18000
TIME-EXTENSION CURVES FOR C-Mo CAST STEELS.
EXTENSION-INCH PER INCH.
TIME-HOURS (HUNDREDS)

FIG.1

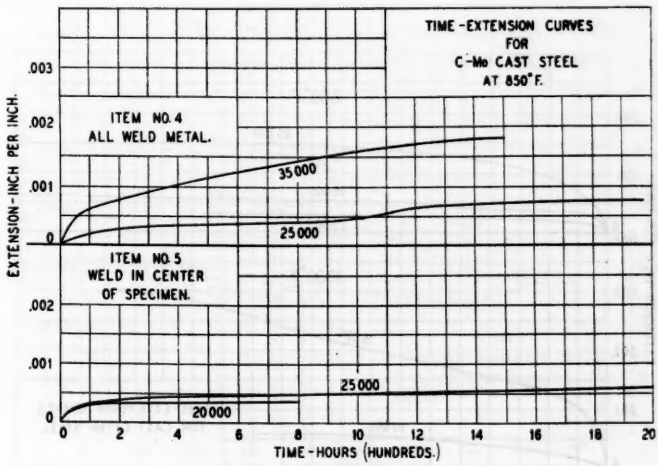

TIME-EXTENSION CURVES FOR C-Mo CAST STEEL AT 850°F.
ITEM NO.4
ALL WELD METAL.
35000
25000
ITEM NO.5
WELD IN CENTER OF SPECIMEN.
25000
20000
EXTENSION-INCH PER INCH.
TIME-HOURS (HUNDREDS.)

FIG. 2

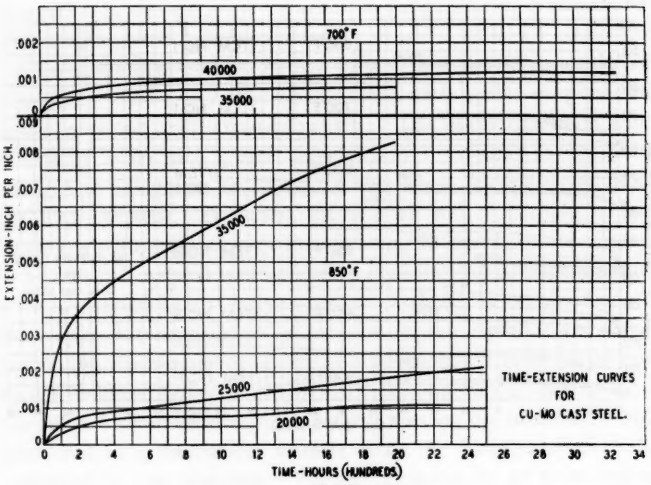

700°F
40000
35000
850°F
35000
25000
20000
TIME-EXTENSION CURVES FOR CU-MO CAST STEEL.
EXTENSION-INCH PER INCH.
TIME-HOURS (HUNDREDS)

FIG. 3

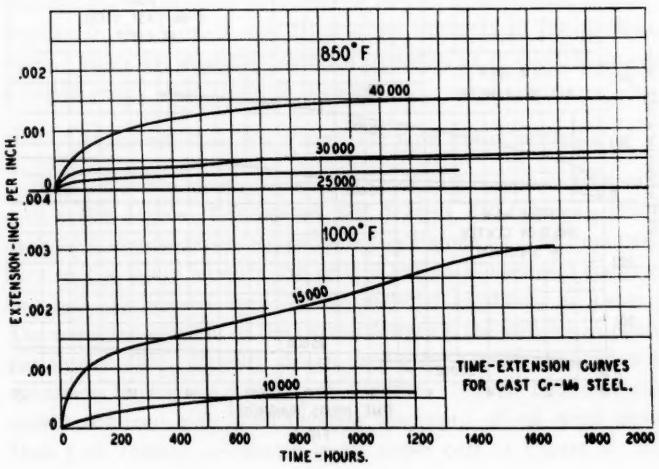

850°F
40 000
30000
25000
1000°F
15000
10000
TIME-EXTENSION CURVES FOR CAST Cr-Mo STEEL.
EXTENSION-INCH PER INCH.
TIME-HOURS.

FIG. 4

curves shown under Item 5 of the same figure were obtained with 2-inch bi-metal specimens, that is, specimens taken across the weld of a test plate. These specimens were prepared from a welded plate following a stress relieving treatment at 1200 degrees F. for four hours. Likewise, all welded assemblies from which specimens were prepared from the base metal were similarly stress relieved. Specimens prepared from the copper-molybdenum and chromium-molybdenum steel plates and the cast coupons, Item 3, were tested in the condition as received.

Similar time-extension relationships for copper-molybdenum cast steel and chromium-molybdenum cast steel are shown in Figures 3 and 4, respectively. The chemical composition of these steels is also given in Table I.

Results of tension and hardness tests for the several materials are given in Table II. The tensile properties for cast carbon-molybdenum steel over a temperature range are shown graphically in Figure 5.

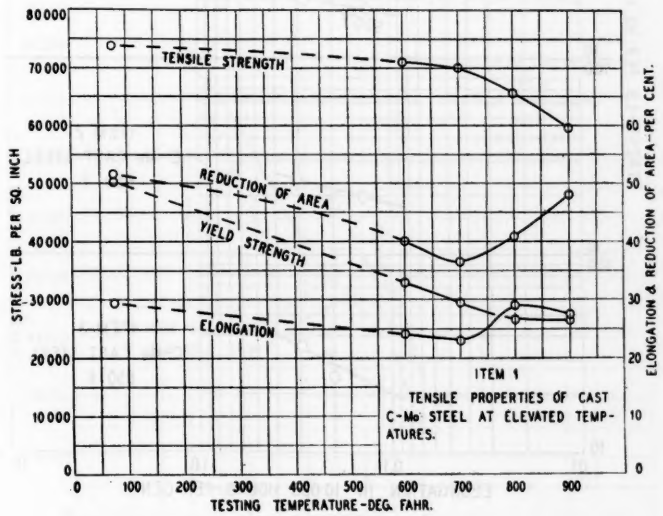


FIG. 5

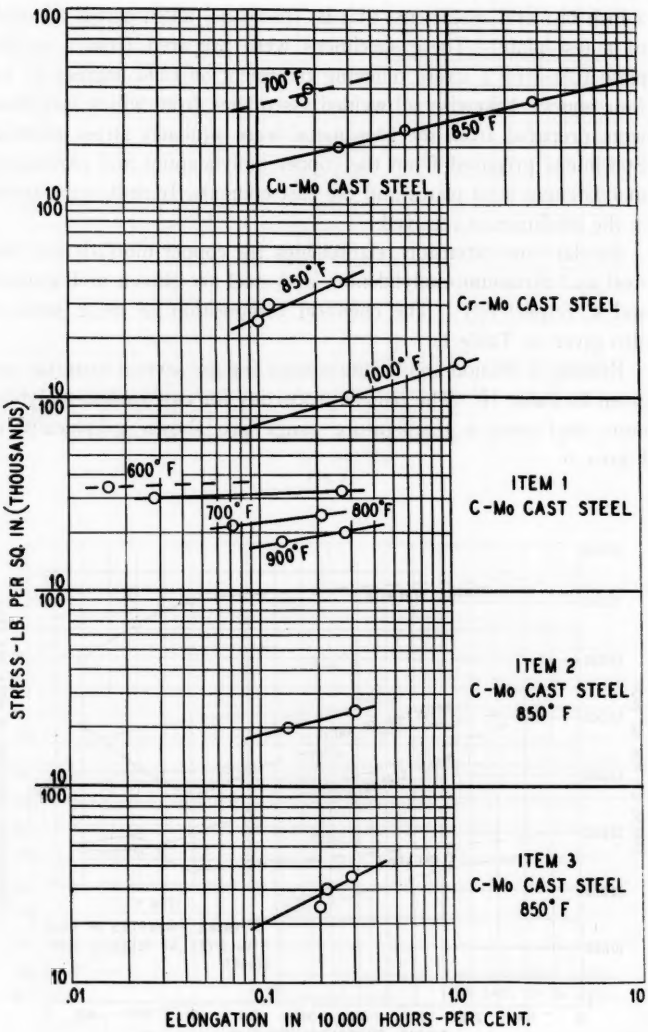

100
700° F
850° F
Cu-Mo CAST STEEL
10
100
850° F
Cr-Mo CAST STEEL
1000° F
10
100
600° F
700° F
800° F
900° F
ITEM 1
C-Mo CAST STEEL
10
100
ITEM 2
C-Mo CAST STEEL
850° F
10
100
ITEM 3
C-Mo CAST STEEL
850° F
10
.01
0.1
1.0
10
STRESS-LB. PER SQ. IN. (THOUSANDS)
ELONGATION IN 10 000 HOURS-PER CENT.

FIG. 6

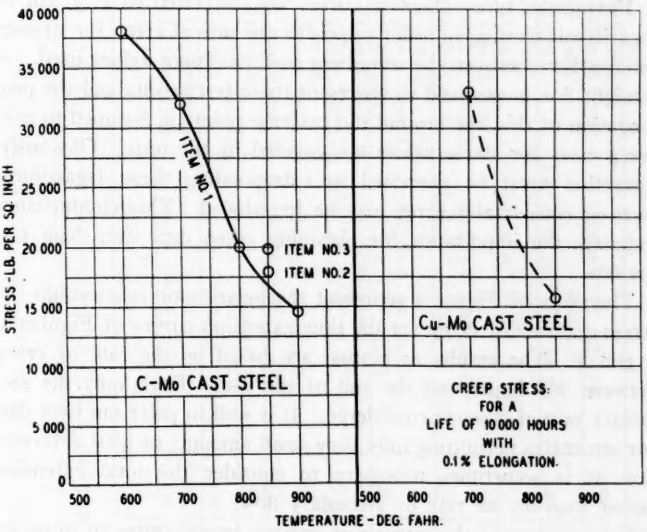

40 000
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
STRESS - LB. PER SQ. INCH
ITEM NO. 1
ITEM NO. 3
ITEM NO. 2
C-Mo CAST STEEL
Cu-Mo CAST STEEL
CREEP STRESS FOR A LIFE OF 10 000 HOURS WITH 0.1 % ELONGATION.
500 600 700 800 900
TEMPERATURE - DEG. FAHR.

FIG. 7

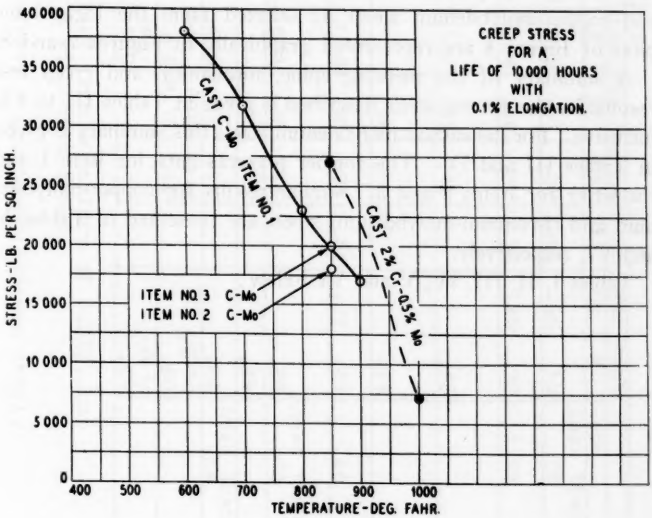

40 000
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
STRESS - LB. PER SQ. INCH.
CREEP STRESS FOR A LIFE OF 10 000 HOURS WITH 0.1 % ELONGATION.
CAST C-Mo ITEM NO. 1
CAST 2 % Cr - 0.5 % Mo
ITEM NO. 3 C-Mo
ITEM NO. 2 C-Mo
400 500 600 700 800 900 1000
TEMPERATURE - DEG. FAHR.

FIG. 8

Frequently, time-extension curves are converted to a system of logarithmic plotting in order to predict the rate of creep for stresses intermediate between the minimum and maximum values used. A straight line is assumed to represent these test results and the prolongation of this line beyond the extreme points is assumed to give creep rates for stress values not covered by the tests. Obviously, discretion must be exercised in extrapolating these logarithmic plots or considerable error may be introduced. This circumstance indicates the importance for obtaining creep data over long test periods.

The plots of Figure 6 represent the logarithmic relationship for stress and rate of creep for the time-extension curves of Figures 1, 3 and 4. The results as plotted are based on the rate of creep between 250 hours and the end of the test. Thus, only the secondary rate of creep is considered. It is well to point out here that for structures permitting only very small amounts of total deformation, it is sometimes necessary to consider the total extension rather than on the rate of secondary flow.

Comparisons of the stresses at various temperatures to cause an extension of 0.1 per cent in 10,000 hours for carbon-molybdenum and copper-molybdenum steels as selected from the logarithmic plots of Figure 6 are represented graphically in Figures 7 and 8.

A summary of the metallographic, mechanical and creep test results for the several steels described is given in Tables III to VI, inclusive. For the carbon molybdenum steels this summary is given in Tables III and IV. The former presents data for Item 1 and the latter for Items 2 and 3. Similar results for copper-molybdenum and chromium-molybdenum steels are presented in Tables V and VI, respectively.

Tables I, II, III, IV, V and VI follow:

TABLE I

Material Designation	Material Shape		Chemical Composition, Per Cent								
			C	S	P	Mn	Si	Ni	Cu	Mo	Cr
Cu-Mo Cast Steel	Plate 12-3/8"x8"x(2"-2-1/4")		.34	.022	.029	.91	.37	None	.86	.18	Less than .08
Cr-Mo Cast Steel	Plate 14-1/4" x 6" x 1"		.18	.038	.024	.42	.81	.26	.36	.70	1.93
Item 1 C-Mo Cast Steel (Base Metal)	Welded Assembly 1-1/4" x 12" x 18"		.22	.026	.029	.81	.43			.45	
Item 2 C-Mo Cast Steel (Base Metal)	Welded Assembly 1" x 12" x 12"		.31			.56	.25			.49	
Item 3 C-Mo Cast Steel	Coupons 3/4" - 7/8" x 1" x 7"		.28	.016	.015	.66	.24	.31	.27	.45	.16
Item 4 C-Mo Cast Steel (All weld metal	Welded Assembly 1" x 12" x 12"		.08	.025	.004	.60	.14			.32	Less than .02
Item 5 C-Mo Cast Steel (Bi-Metal)	Ditto	Base Metal	.31			.56	.25			.49	
		Weld Metal	.08	.025	.004	.60	.14			.32	Less than .02
Navy Department Specification SGS(1)-110a	Base Metal		Max. .35*	Max. .04	Max. .04	.50 to *.70	.20 to .45			.40 to .60	
	ø Weld Metal			Max. .045	Max. .040					.40 to .60	

* For each reduction of 0.01% carbon content from a maximum of 0.35%, an increase of 0.025% manganese above 0.70% will be allowed.

ø Instructions for Approval of Welding Process - Carbon-Molybdenum Steel.

TABLE II
TENSION AND HARDNESS TESTS

Material Designation	Material Shape	Testing Temp. °F.	Tensile Strength	Yield	Johnson's Limit	Proof Stress	Elastic Limit	Proport'l Limit	El. in 2"	Red. of Area	Brinell Hardness No.
			Pounds per Square Inch						Per cent		
Cu-Mo Cast Steel	Plate 12-3/8"x8"x (2"-2-1/4")		86750	57000	55000	50000	27500	25000	23.5	45.5	
		76	87000	54000	50000	51400	25000	20000	25.3	51.7	174
		Avg.	86900	55500	52500	50700	26250	22500	24.4	48.6	
Cr-Mo Cast Steel	Plate 14-1/4"x 6"x 1"		117000	76600	70000	70000	65000	49000	15.8	37.6	
		76	100900	75500	70000	68000	60000	54000	21.9	55.9	179
		Avg.	109000	76050	70000	69000	62500	51500	18.9	46.8	
Item 1 C-Mo Cast Steel (Base Metal)	Welded Assembly 1-1/4"x12"x18"		74400	52500	50500	51500	50000	47500	29.5	49.7	
		76	74300	50000	49000	49500	48700	44000	30.0	53.4	149
			72800	48750	47500	48500	47500	43500	29.5	52.8	
			73900	50000	48700	49000	47500	45000	28.5	50.6	
		Avg.	73850	50300	48900	49600	48400	45000	29.4	51.6	
		600	71000	32800	30200	-	-	29000	24.0	40.0	
		700	70000	29500	25500	-	-	25000	23.0	36.5	
			65300	25800	20000	-	-	19000	28.4	35.5	
		800	65500	27500	21500	-	-	20000	29.7	46.0	
		Avg.	65400	26650	20750	-	-	19500	29.1	40.8	
			58750	26500	20000	-	-	18000	*	*	
		900	60650	26500	20000	-	-	18500	27.3	48.0	
		Avg.	59700	26500	20000	-	-	18250			
Item 2 C-Mo Cast Steel (Base Metal)	Welded Assembly 1" x 12" x 12"		85000	59000	59000	58000	57500	54000	22.0	37.9	
		76	88250	59500	59000	59000	58500	54000	21.5	35.4	152
		Avg.	86600	59250	59000	58500	58000	54000	21.8	36.7	
Item 3 C-Mo Cast Steel	Coupons 3 4"-7/8"x1"x7"	76	85750	68000	65000	64500	60000	48000	25.7	50.0	177
		850	71250	42200	34000	-	-	30000	22.8	46.8	
Item 4 C-Mo Cast Steel (All Weld Metal)	Welded Assembly 1" x 12" x 12"		68500	-	55000	55500	55000	50000	30.5	60.3	
		76	68500	-	54000	55000	53750	52500	32.5	64.5	144
		Avg.	68500	-	54500	55250	54380	51250	31.5	62.4	
Item 5 C-Mo Cast Steel (Bi-Metal)	Welded Assembly 1" x 12" x 12"		ø75300	-	-	-	-	-	18.0	23.4	
		76	ø75900	-	-	-	-	-	12.5	18.7	-
		Avg.	75600	-	-	-	-	-	15.3	21.1	
Navy Dept. Spec. SGS(1)-110a	Base Metal		Minimum 70000	-	-	Minimum 35000	-	-	Minimum 20.0	30.0	
	Weld Metal		65000			40000			20.0		

* Broke outside punch marks.
ø Flat specimen.- fractured partly in weld and partly in fusion zone.

SUMMARY

Physical Properties Obtained	T.S. lbs./ sq.in.	% long in 2
Before Creep Test	73850	29.
After Creep Test	74200	35.
After Creep Test	74400	31.
After Creep Test	-	-
After Creep Test	77300	27.
After Creep Test	-	-
After Creep Test	73700	34.

TABLE III

SUMMARY OF METALLOGRAPHIC, MECHANICAL, AND CREEP TEST RESULTS FOR CAST C-MO STEEL

T.S. lbs./sq.in.	%long. in 2" %	Red. of Area %	Microstructure	Grain Size *	Creep Test Data: Test. Temp. deg.F	Stress lbs./sq.in.	Time hrs.	Total Creep, in./in.	Avg.Creep for past interval, in./in./hr x 10^{-6}	Creep Rate % elong.in 10^4 hrs.	Years to give - % creep for creep rate between hrs.indicated .01%	0.1%	1.0%
					Item 1								
73850	29.4	51.6	Normal microstructure for cast C-Mo steel of this type.	7 to 8	-	-	-	-	-	-	-	-	-
							250	.00060	2.40				
							500	.00060	0				
							750	.00061	.04				
74200	35.0	57.2	-	-	600	35000	1000	.00061	0	.016	.714	7.14	71.4
							1500	.00063	.04				
							2000	.00065	.04				
							2500	.00065	0				
							3000	.00065	0				
							3340	.00065	0				
							250	.00018	0.72				
							500	.00018	0				
							750	.00019	.04				
74400	31.0	59.1	-	-	700	30000	1000	.00020	.04	.028	.408	4.08	40.8
							1500	.00020	0				
							2000	.00022	.04				
							2500	.00024	.04				
							3000	.00025	.02				
							3500	.00029	.08				
							4000	.00030	.02				
							4450	.00030	0				
							250	.00048	1.92				
							500	.00072	.96				
							750	.00084	.48				
-	-	-	-	-	700	33000	1000	.00086	.08	.27	.042	.42	4.2
							1500	.00091	.10				
							2000	.00097	.12				
							2112	.00099	.17				
							250	.00048	1.92				
							500	.00051	.12				
							750	.00056	.20				
77300	27.5	46.9	Normal microstructure for cast C-Mo steel of this type	7 to 8	800	25000	1000	.00072	.64	.21	.054	.54	5.4
							1500	.00080	.16				
							2000	.00090	.20				
							2500	.00095	.10				
							250	.00041	1.64				
							500	.00053	.48				
-	-	-	-	-	900	18000	750	.00057	.16	.13	.088	.88	8.8
							1000	.00062	.20				
							1500	.00064	.04				
							2136	.00066	.03				
							250	.00108	4.32				
							500	.00131	.92				
							750	.00137	.24				
73700	34.0	57.0	-	-	900	20000	1000	.00140	.12	.28	.041	.41	4.1
							1500	.00145	.10				
							2000	.00149	.36				
							2500	.00172	.18				
							2900	.00182	.25				

*{Grain Size No.7 - 48 to 96 grains per sq.in. at 100 diameters.
" " " 8 - 96 and more " " " " " "

SUMMARY OF METALLOGRA

Physical Properties Obtained	T. S. lbs./ sq.in.	Elong. in 2" %	Red. of Area %	Micro
Before Creep Test	86600	21.8	36.7	Fairly distri consti minute plates within grains
After Creep Test	78900	♯ 8.9	25.4	
After Creep Test	-	-	-	Fairly distri consti minute plates within grains
After Creep Test	85750	25.7	50	Uniform bution stitue ferrite visible pearlit
After Creep Test	89500	26.6	52.2	
After Creep Test	86750	27.5	54.1	
After Creep Test	-	-	-	Uniform bution stitue ferrite visible pearlit

*(Cr

♯ Fr

TABLE IV

METALLOGRAPHIC, MECHANICAL, AND CREEP TEST RESULTS FOR CAST C-MO STEEL

ed. of rea %	Microstructure	Grain Size *	Creep Test Data: Test. Temp. deg.F	Stress lbs./ sq.in.	Time hrs.	Total Creep, in./in.	Avg.Creep for past interval, in./in./hr. x 10^{-6}	Creep Rate % elong.in 10^4 hrs.	Years to give - % creep for creep rate between hrs.indicated .01%	0.1%	1.0%
	Item 2										
6.7	Fairly uniform distribution of constituents; minute ferrite plates visible within pearlite grains.	7	-	-	-	-	-	-	-	-	-
					250	.00015	0.60				
					500	.00022	0.28				
5.4	-	-	850	20000	750	.00025	0.12	0.14	.082	.82	8.2
					1100	.00027	0.057				
					250	.00088	3.52				
	Fairly uniform distribution of constituents; minute ferrite plates visible within pearlite grains.	7	850	25000	500	.00110	.88				
					750	.00122	.48				
-					1000	.00126	.16	0.31	.0036	.036	.36
					1500	.00135	.18				
					2000	.00142	.14				
	Item 3										
50	Uniform distribution of constituents; small ferrite plates visible within pearlite grains.	8	-	-	-	-	-	-	-	-	-
					250	.00033	1.32				
					500	.00043	.40				
2.2	-	-	850	25000	750	.00046	.12	.20	.057	.57	5.7
					1080	.00050	.12				
					250	.00075	3.00				
					500	.00085	.40				
4.1	-	-	850	30000	750	.00091	.24	.22	.052	.52	5.2
					1000	.00096	.20				
					1400	.00100	.10				
					250	.00102	4.08				
	Uniform distribution of constituents; small ferrite plates visible within pearlite grains.	8	850	35000	500	.00120	.72				
-					750	.00130	.40	.29	.039	.39	3.9
					1000	.00137	.28				
					1500	.00150	.26				
					2090	.00155	.08				

*(Grain Size No.7 - 48 to 96 grains per sq.in. at 100 diameters
(" " " 8 - 96 & more " " " " " "

$ Fracture occurred outside punch marks and revealed a casting flaw.

T

SUMMARY OF METALLOGRAPHIC, MECHA

Physical Properties obtained	T.S. lbs./ sq.in.	Elong. in 2" %	Reduct. of area %	Microstructure
Before Creep Test	86750	23.5	45.0	Fairly uniform grain size with uniform distribution of constituents. Large pearlite grains are broken up by membranes of ferrite.
	87000	25.3	51.7	
Average	86900	24.4	48.6	
After Creep Test	91000	14.5	22.3	Fairly uniform grain size. Few large grains of pearlite.
After Creep Test	94200	15.5	22.0	Uniform grain size. Large pearlite grains, dispersed.
After Creep Test	86500	12.5	11.9	Fairly uniform grain size. Few large grains of pearlite.
After Creep Test	-	-	-	-
After Creep Test	86700	25.0	50.1	Fairly uniform grain size. Few large grains of pearlite.

*(Grain Size No. 2 - 1-1/2 to 3 grains per sq.in
" " " 4 - 6 to 12 " " "
" " " 5 - 12 to 24 " " "

TABLE V

HIC, MECHANICAL, AND CREEP TEST RESULTS FOR CAST CU-MO STEEL

re	Grain Size #	Creep Test Data: Testing Temp. deg.F	Stress lbs/sq.in.	Time, hrs.	Total Creep, in./in.	Avg. for past interval, in./in/hr. x 10^{-6}	Creep Rate per cent elongation in 10^4 hours	Years to give - % creep for creep rate between hours indicated: .01%	0.1%	1.0%
n size bution of pearlite p by e.	2 to 4	-	-	-	-	-	-	-	-	-
n size. pearl-	4 to 5	700	35000	250 500 750 1000 1500 2000	.00048 .00060 .00069 .00070 .00075 .00077	1.92 .48 .36 .04 .10 .04	0.17	.067	.67	6.7
. Large ispersed.	4 to 5	700	40000	250 500 750 1000 1500 2000 2500 3000 3200	.00069 .00085 .00090 .00098 .00105 .00113 .00117 .00120 .00121	2.76 .64 .20 .32 .14 .16 .08 .06 .05	.18	.063	.63	6.3
n size. pearl-	4	850	20000	250 500 750 1000 1500 2000 2300	.00057 .00075 .00078 .00080 .00095 .00108 .00110	2.28 .72 .12 .08 .30 .26 .07	.27	.042	.42	4.2
	-	850	25000	250 500 750 1000 1500 2000 2460	.00082 .00099 .00113 .00129 .00157 .00185 .00213	3.28 .68 .56 .64 .56 .56 .61	.59	.019	.19	1.9
n size. pearl-	4 to 5	850	35000	250 500 750 1000 1500 2000	.00387 .00480 .00547 .00613 .00742 .00879	15.48 3.72 2.68 2.64 2.58 2.74	2.81	.0041	.041	.41

per sq. in.
" "

TABLE VI

SUMMARY OF METALLOGRAPHIC, MECHANICAL, AND CREEP TEST RESULTS FOR CAST CR-MO STEEL

Specimen Number	Physical Properties Obtained	T. S. lbs./sq.in.	Elong. in 2" %	Red. of Area %	Microstructure	Grain Size *	Creep Test Data: Test Temp. deg.F	Stress lbs./sq.in.	Time hrs.	Total Creep, in./in	Avg. Creep for past interval, in./in./hr. x 10 $^{-6}$	Creep Rate % elong. in 10^4 hrs.	Years to give - % creep for creep rate between hrs. indicated .01%	0.1%	1.0%
APM 3550 APM 3535	Before Creep Test	117000	15.8	37.6	Variable grain size; semi-sorbitic structure	6 to 7	-	-	-	-	-	-	-	-	-
	Average	109000	18.9	46.8											
APM 3520	After Creep Test	100500	25.3	55.3	-	-	850	25000	250	.00019	.76	.099	.114	1.14	11.4
									500	.00023	.16				
									750	.00025	.08				
									1000	.00030	.20				
									1364	.00030	0				
APM 3510	After Creep Test	99500	16.4	26.8	-	-	850	30000	250	.00038	1.52	.114	.100	1.00	10.0
									500	.00040	.08				
									750	.00050	.40				
									1000	.00054	.16				
									1500	.00056	.04				
									2000	.00058	.04				
APM 3720	After Creep Test	-	-	-	Variable grain size; semi-sorbitic structure	6 to 7	850	40000	250	.00103	4.12	.268	.042	.42	4.2
									500	.00125	.88				
									750	.00137	.48				
									1000	.00145	.32				
									1500	.00150	.10				
									2000	.00150	0				
APM 3710	After Creep Test	92300	15.0	25.2	-	-	1000	10000	250	.00032	1.28	.295	.039	.39	3.9
									500	.00045	.52				
									750	.00054	.36				
									1000	.00059	.20				
									1200	.00060	.05				
APM 3500	After Creep Test	-	-	-	Variable grain size; semi-sorbitic structure	6 to 7	1000	15000	250	.00137	5.48	1.147	.0099	.099	.99
									500	.00167	1.20				
									750	.00174	.28				
									1000	.00225	2.04				
									1500	.00295	1.40				
									1688	.00302	.37				

*{Grain Size No.6 - 24 to 48 grains per sq.in. at 100 diameters
" " " 7 - 48 to 96 " " " " " "

RESULTS OF SOME CREEP TESTS FOR CAST COMPOSITION BRONZES.

Figure 9 presents time-extension graphs for Composition "G" alloy in the form of 2-inch gauge length cast-to-size tension specimens. Similar graphs for specimens machined from a large cast

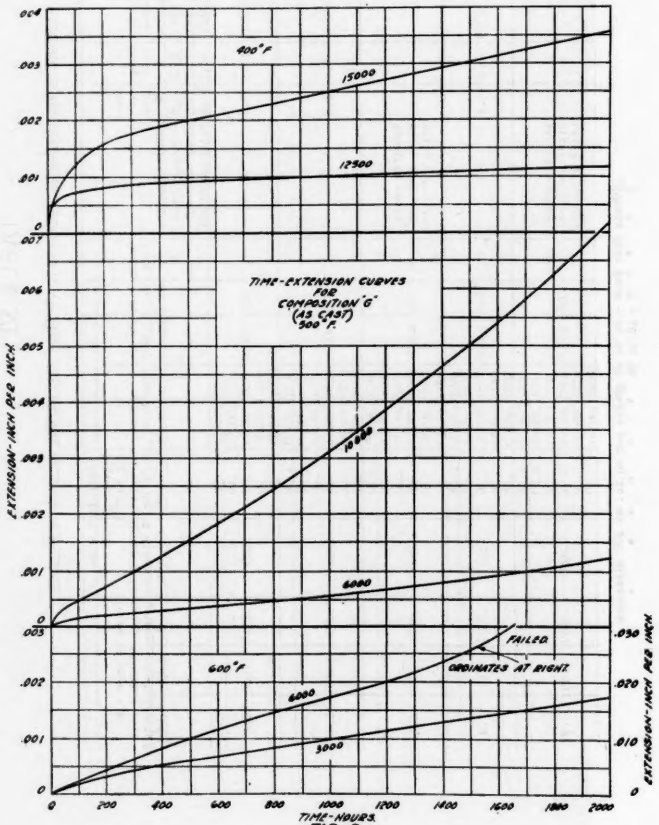


FIG. 9

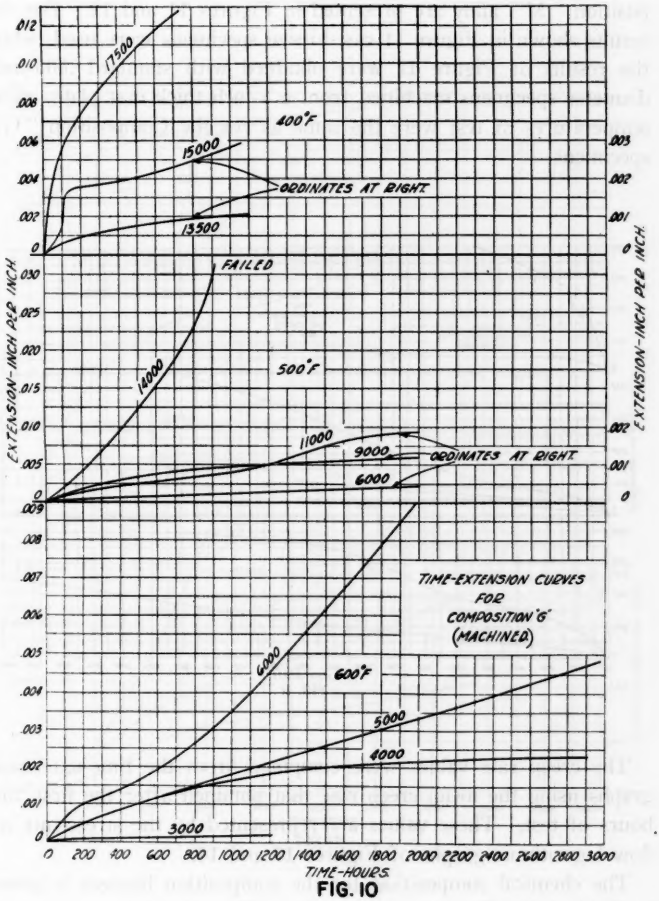

EXTENSION-INCH PER INCH
EXTENSION-INCH PER INCH
TIME-HOURS
400°F
500°F
600°F
17500
15000
13500
14000
11000
9000
6000
5000
4000
3000
FAILED
ORDINATES AT RIGHT
ORDINATES AT RIGHT
TIME-EXTENSION CURVES FOR COMPOSITION 'G' (MACHINED)

FIG. 10

sleeve taken from a propeller shaft are shown in Figure 10. For both series of graphs, temperatures of 400 degrees, 500 degrees and 600 degrees F. were investigated. Corresponding graphs for Composition " M " alloy are presented in Figures 11 and 12. For the results shown in Figure 11 cast-to-size specimens were used, while the results of Figure 12 were obtained with standard .505-inch diameter specimens machined from a 1-inch thick cast plate. The temperatures of test were the same as for the Composition " G " specimens.

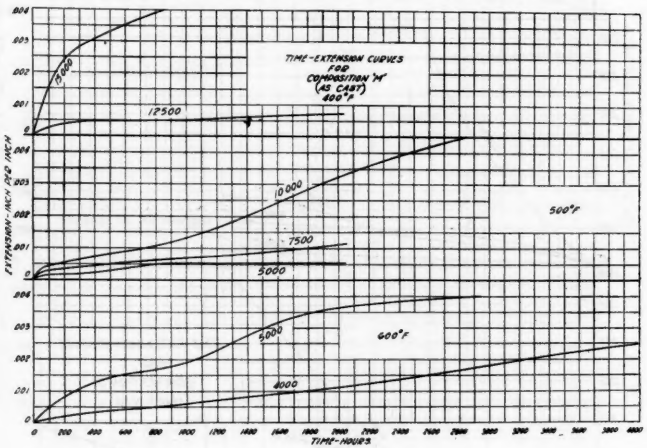


FIG. 11

The creep rate values were computed from the time-extension graphs using the mean creep rate that obtained after the first 250 hours of test. These values are represented by the stress-rate of flow logarithmic graphs of Figures 13 and 14.

The chemical composition for the composition bronzes is given in Table VII; Tension and Hardness Test Results are given in Table VIII.

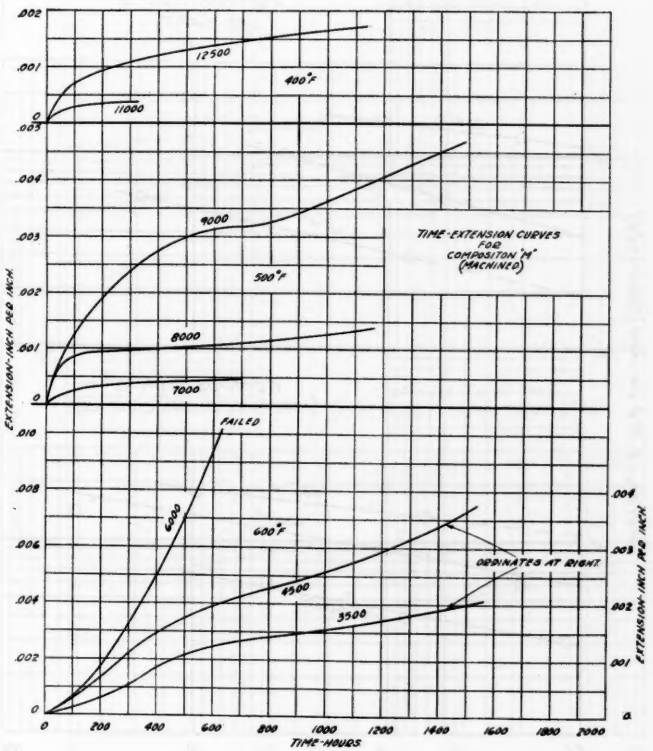

TIME-EXTENSION CURVES FOR COMPOSITION "A" (MACHINED)
12500
11000
400°F
9000
8000
7000
500°F
FAILED
6000
600°F
4500
3500
ORDINATES AT RIGHT
EXTENSION-INCH PER INCH
TIME-HOURS
0
200
400
600
800
1000
1200
1400
1600
1800
2000
.002
.001
.003
.004
.005
.006
.007
.008
.009
.010

FIG. 12

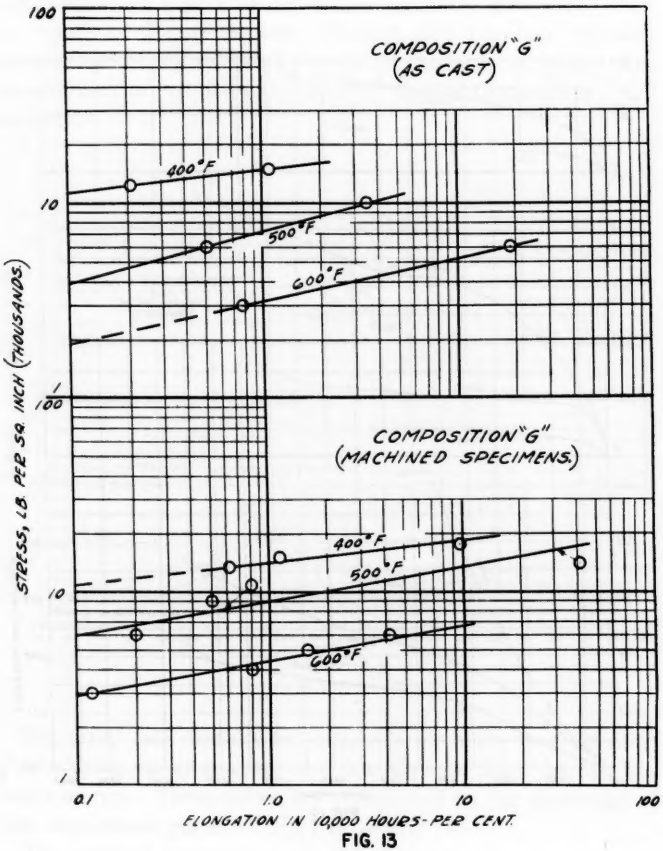

COMPOSITION "G"
(AS CAST)
400°F
500°F
600°F
COMPOSITION "G"
(MACHINED SPECIMENS.)
400°F
500°F
600°F
100
10
1
1/100
STRESS, LB. PER SQ. INCH (THOUSANDS)
0.1
1.0
10
100
ELONGATION IN 10,000 HOURS - PER CENT.

FIG. 13

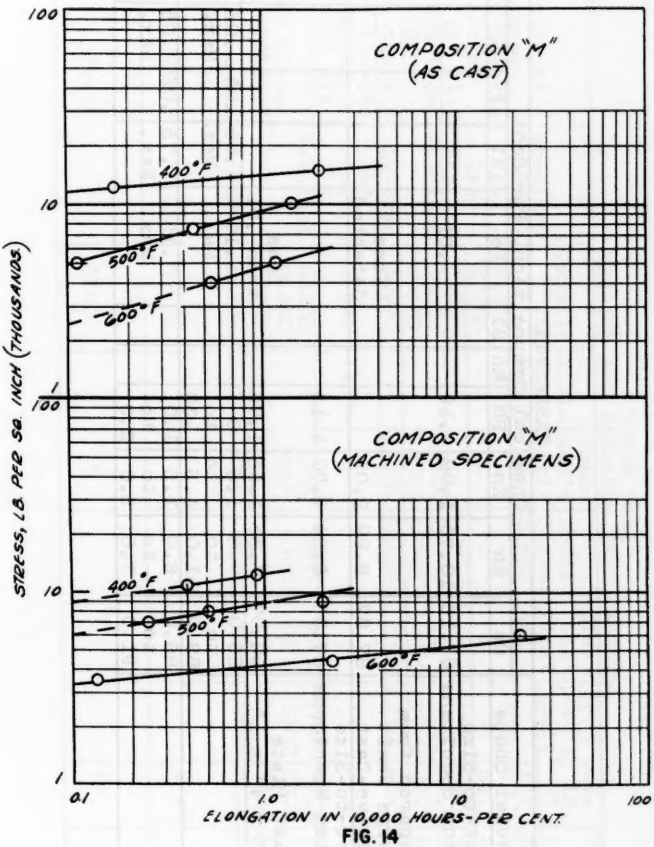

COMPOSITION "M"
(AS CAST)
400°F
500°F
600°F
COMPOSITION "M"
(MACHINED SPECIMENS)
400°F
500°F
600°F
100
10
1
1/100
10
1
0.1
1.0
10
100
STRESS, LB. PER SQ. INCH (THOUSANDS)
ELONGATION IN 10,000 HOURS-PER CENT.

FIG. 14

TABLE VII

Material	Material Shape	Chemical Composition, Per Cent											Other Elements
		Cu	Sn	Zn	Pb	Mn	Si	Fe	Ni	P	S	Sb	
Composition "G"	Cast-to-Size Tension Specimens	87.16	10.70	1.98	.19			.02					
	Prepared from Large Shaft Sleeve-Cast	87.87	9.89	2.09				None detected					
Composition "M"	Cast-to-Size Tension Specimens	87.33	6.84	4.70	1.15								
	Cast Plate 12" x 4" x 1"	90.07	6.33	1.85	1.75			Less than .01					
Comp."G" N.D.Spec. 46M6e		86.0 to 89.0	7.5 to 11.0	1.5 to 4.5	0 to .30			.10 Max.	.75 Max.	.05	.05 Max.	.25 Max.	.15 Max.
Comp."M" N.D.Spec. 4688e		86.0 to 91.0	6.0 to 7.0	1.5 to 5.0	1.0 to 2.0			.15 Max.	.75 Max.	.05	.05 Max.	.25 Max.	.15 Max.

TABLE VIII

TENSION AND HARDNESS TEST RESULTS

Material	Material Shape	Specimen Condition	Tensile Strength	Yield	Johnson's Limit	Proof Stress	Elastic Limit	Prop't'l Limit	El. in 2"	Red. of Area	Brinell Hardness Number
			Pounds per Square Inch						Per Cent		
Composition "G" - Cast	Cast-to-size tension 6"x .8" dia.	As Cast	41500	15900	-	-	-	6500	32.1	28.5	64
			40500	-	-	-	-	-	24.1	22.7	
		Average	41000	-	-	-	-	-	28.1	25.6	
	Sleeve from USS IDAHO tube shaft	Machined	30000	-	11500	12000	9500	6000	20.5	24.7	55
			30150	-	12000	12300	10000	5500	22.5	25.1	
		Average	30080	-	11750	12150	9750	5750	21.5	24.9	
Composition "M" - Cast	Cast-to-size tension 6"x .8" dia.	As Cast	39500	14800	-	-	-	-	30.5	26.7	55
	Cast Plate 12"x 10"x 1"	Machined	26250	-	8500	8500	6500	5000	17.5	13.7	49
			28650	-	8300	8700	6300	5300	22.0	19.9	
			30900	-					21.5	16.7	
		Average	28600	-	8400	8600	6400	5150	20.3	16.8	
Comp."G" Navy Spec. 46M6e	Cast		40000						20.0		
Comp."M" Navy Spec. 46B8e	Cast		32000						17.0		

DISCUSSION.

The tensile strength of the cast carbon-molybdenum and copper-molybdenum steels has not been altered materially as a result of the creep test temperatures and stresses used. The ductility for the copper-molybdenum steel falls off considerably following the creep tests; while this property for the carbon-molybdenum steels is not changed appreciably. Results of tensile tests for the cast chromium-molybdenum steel following creep tests at 850 degrees F. temperature have shown no material change from the normal tensile values. However, tensile tests following creep tests at 1000 degrees F. temperature show that the tensile strength and ductility have been reduced somewhat below the normal values.

Both the Composition " G " and " M " alloys have shown considerable reduction in tensile and ductile properties when tested after removal from the creep test furnaces, the maximum reduction being noted for the latter alloy. Coarsening of the grain structure was noted for both materials after prolonged heating at 600 degrees F. Accordingly, the use of these materials beyond the temperature range 450 degrees to 500 degrees F. is not indicated.

The creep curves of Figures 1 to 4, inclusive, are characterized by a rapid initial rate of flow followed by a secondary rate of flow which remains fairly constant. Curves of this type show that the material has been strengthened during the test; otherwise, the initial creep rates would have continued. At higher temperatures creep curves may show a third stage where the creep rate is accelerated, resulting in necking down of the specimen followed by rupture. Apparently, there is a critical temperature for a metal at or below which the creep rate diminishes after the primary flow and above which the creep rate increases for given stress values. This critical temperature is called the equicohesive temperature and may be defined as the temperature at which the cohesion of the amorphous and crystalline phases are equal. Creep investigators usually refer to the equicohesive temperature without being very definite as to what this temperature is. Since the percentage of amorphous material varies with the grain size, which in turn may be altered by cold working, it is evident that materials of similar chemical composition may differ as regards the equicohesive temperature. However, this temperature corresponds with the lowest tempera-

ture of recrystallization. At or below this temperature strain-hardening is the controlling factor and creep rates will diminish unless the stresses are so high as to overcome the strain-hardening effects. At temperatures above the equicohesive temperature, creep will proceed under the lowest stresses. Hence, the minimum temperature at which a constant rate of creep occurs should correspond to the temperature at which the beneficial effects of strain-hardening are balanced by recrystallization.

While good resistance to creep is very important for a material which is to be used for high temperature service, other properties are also necessary. The material must have satisfactory tensile, fatigue and impact strength. For some types of service, considerable resistance to corrosion, erosion and oxidation is required. Moreover, the material must retain its structural stability at the temperature used for a long period of time. Lack of structural stability may manifest itself in various ways, for example, alteration in grain size, spheroidization of carbides and precipitation of carbides at the grain boundaries. Since most high temperature equipment is more or less complicated in shape, it is necessary that the material be workable so that it can be fabricated at reasonable cost. With the developments in welding during recent years, it is desirable that the material be readily weldable.

Unfortunately, all these properties are not possessed to the maximum degree by any one material. Hence, it is necessary that the engineer select the material with reference to the most important high temperature properties required in the particular installation.

In this connection, it may be pointed out that carbon-molybdenum steel possesses good high-temperature properties at 1000 degrees F., being much superior to plain carbon steel as regards creep strength. However, this alloy shows no superiority over plain carbon steel as regards resistance to oxidation at 1000 degrees F. Consequently, carbon-molybdenum steel can only be used to advantage over plain carbon steel for conditions where creep resistance and not resistance to scaling is of primary importance. For maximum resistance to scaling at temperatures up to 1000 degrees F., the use of steels of the 4 per cent-6 per cent chromium-.5 per cent molybdenum type is indicated. This steel has about twice the creep strength of carbon steel at 1000 degrees F. temperature and decidedly superior scale resistance. However, this steel exhibits air hardening characteristics and

can be welded satisfactorily only when preheated. It is reported that the air hardening characteristics of the steel can be overcome by suitable additions of titanium or columbium. However, the Station has not investigated the 4 per cent-6 per cent chromium steels having these alloy additions.

Steel containing about 2.0 per cent chromium, 0.80 per cent silicon and 0.5 per cent molybdenum possesses good creep strength combined with fairly good resistance to oxidation up to 1000 degrees F. Materials of this type have higher tensile and elastic properties at both normal and elevated temperatures than has the 4 per cent-6 per cent chromium steel. Consequently, this type of material is more suitable for use as high temperature bolts and studs.

The austenitic chromium-nickel steels containing about 18.0 per cent chromium and 8 per cent nickel possess a combination of properties which make these alloys very suitable for many high temperature applications. Embrittlement may incur in these alloys when used within the temperature range 950 to 1500 degrees F. Embrittlement of the material may also result from welding temperatures, unless the welded structure is water quenched from about 1850 degrees F. after welding. For many structures this procedure is not practicable. Under these conditions, relatively small percentages of titanium and columbium are added to "stabilize" the material. Molybdenum additions improve the resistance to corrosion. The 18:8 alloys are highly resistant to oxidation up to temperatures of 1800 degrees F. However, the material may be attacked by sulphur gases under some conditions. Records show that steam pipes of this alloy have been used at 1100 degrees F. temperature for a number of years.

It will be seen that the problem of suitable metals for high temperature service is a complex one. Demands for metals to withstand increasing pressures, temperatures and corrosive conditions are being made constantly by the power, oil refining and chemical industries. Likewise, the necessity for higher steam pressure and temperatures in the Navy has created a demand for metals suitable for this type of service. The high temperature problems of the Navy are further complicated by restrictions as regards space and weight.

NOTES.

INDEX TO NOTES.

SPECIAL NOTICE.

TORPEDO CRAFT.
—The Engineer, London, England, October 29, 1937.

TORCH HARDENING OF GEAR TEETH.
—Machinery, New York, N. Y., November, 1937.

SHIP PROPULSION BY THE EMMET-MERCURY-VAPOR PROCESS.
—Shipbuilding and Shipping Record, London, England, November 25, 1937.

DAMAGE TO H. M. S. "HUNTER."
—Transactions, Institution of Engineers and Shipbuilders in Scotland, December, 1937.

MISCELLANEA OF INTEREST TO NAVAL ENGINEERS.

A New Era on the Sea.
—Mechanical Engineering, New York, N. Y., January, 1938.

Industrial Uses for Silver.
—Technical News Bulletin of the National Bureau of Standards, Washington, D. C., January, 1938.

Pyrotenax Electric Cables.
—Shipbuilding and Shipping Record, London, England, October 28, 1937.

Lubricating Oil for Circulating Systems of Steam Turbines.
—Combustion, New York, N. Y., December, 1937.

Heavy Tungsten Alloy.
—Engineering, London, England, December 3, 1937.

Metals Battle Hot Water and Steam.
—Power, New York, N. Y., Mid-December, 1937.

SPECIAL NOTICE.

On pages 607-615 of the November issue of the A. S. N. E. JOURNAL a summary of a paper by Dr. D. R. Pye entitled "Metallurgy and the Aero Engine" was incorrectly credited to The Engineer of London, England. This paper representing the Autumn Lecture read before the Institute of Metals was originally published in the Journal of the Institute of Metals, September, 1937. The opportunity is therefore taken to make a correct designation and acknowledgment of the source for which the article was quoted and to inform the readers of the JOURNAL that this valuable paper in its entirety may be obtained in the Monthly Journal of the Institute of Metals, 36 Victory Street, Westminster, London, England, at a cost to non-members of 10s per copy.

TORPEDO CRAFT.

The following article reprinted from The Engineer, London, England, October 29, 1937, represents an abstract from the Presidential address to the Institution of Mechanical Engineers delivered by Sir John E. Thornycroft on October 22, 1937. The paper is both an historical and technical outline of the development not only of British naval torpedo craft but also of contemporary naval vessels of other classes. The author's admonition for simplicity in naval equipment is the subject of an interesting editorial entitled "Monstrously Ingenious" also appearing in the same issue of "The Engineer" and which is reproduced herewith, following the article itself.

Early torpedo boats were divided into two distinct classes, boats which were supposed to be large enough to keep at sea, and on which the crews could live, and smaller ones (called second-class), which were carried on the decks of the larger warships like her other boats, and could be hoisted out to make their attack when the opportunity arose. The idea of taking flotillas of small boats for attack in distant places was developed, and special carriers, or mother ships, of different designs were built.

In early days the range of guns and rapidity of fire were not very great, and the torpedo boat was regarded as an undoubted menace to the battleship and cruiser, with the result that the Continental navies built them in large numbers, and the sea-keeping types were increased in size and speed from year to year.

By 1892 the French Navy had such large numbers that the British Admiralty came to the conclusion that it was necessary to build some considerable class of vessel specially to combat them (the torpedo gunboats and other classes having proved unsatisfactory), and decided that what was in reality a larger and faster torpedo boat, armed with guns, would be best for the purpose. For the want of a better name, this class were called torpedo-boat destroyers, or "T. B. D.'s."

Of course, foreign navies very soon began to build similar craft. The smaller torpedo boats were no longer built in any numbers and the destroyers were fitted with a powerful torpedo armament, as well as guns, so that they were able to perform the old *rôle* of the torpedo boats as well as fight each other with their gun armament.

By 1914 the destroyer had developed to a vessel of about 1000 tons and 30,000 H.P., carrying 4-inch guns and 21-inch torpedoes. It is obvious that, during the thirty-eight years that had elapsed since the *Lightning*, the No. 1 Torpedo Boat of the British Navy, was built nearly sixty years ago, mechan-

ical engineers, not only in this country, but abroad, must have been very actively employed to have produced boats equipped with so many new developments and giving such good performances.

It is generally easier to experiment on a comparatively small scale. It certainly happened that all the major changes which have taken place in the propelling machinery of ships during the last half-century were first tried and developed in torpedo boats and destroyers. Closed stokeholds, forced draught, water-tube boilers, and steam turbines will occur to everyone. Later on, I will say something about other things, and some of the difficulties that had to be overcome before they were successful.

I will mention now two items which may seem rather trivial in themselves, but which were quite novel at the time they were designed for use with these first torpedo boats, namely, a window wiper for the conning towers, which acted in the same way as those in use on every car today, and a self-draining valve, which would allow the water to run out of the bilge when the boat was travelling at high speed, which is fitted in enormous numbers in high-speed launches today.

You may be interested to know how the idea of running the water through a suitable aperture in the bottom originated. Some of the very earliest torpedo boats had been in action, and rifle bullets (which were of considerable diameter in those days) were fired from the high side of the deck of the vessel which was being attacked, down through the bilge plates of the torpedo boat. The torpedo boats succeeded in getting away, and those on board were surprised to find that, while there were a number of holes in the bottom of the boat, the water did not flow in when she was travelling at a high speed. Hence arose the idea of the patent of the automatic bilge bailer.

While not overlooking the part played by the naval architect, I think mechanical engineers may be regarded as mainly responsible for the very great increases in speed and efficiency of ships that have been so remarkable in the last half-century.

The launch *Miranda,* built in 1870, and a rather larger boat, the *Gitana,* built a year or two after, may be looked upon as the forerunners of the torpedo boat. The *Miranda* had a speed of 18 M.P.H., which was about double that of the average launch of the same dimensions. Inasmuch as she was non-condensing, and the draught was produced by the blast in the funnel and the boiler fed by an injector, her machinery was very similar to a locomotive. Sister boats were used in the Russo-Turkish War in 1876.

The *Lightning,* the No. 1 Torpedo Boat of the British Navy, was a mere modification of the *Gitana.* The *Lightning* was a vessel 81 feet in length, of 400 I.H.P., and about 30 tons displacement, and a speed of 18½ knots, the engines running at 350 R.P.M. To give this performance about 100 pounds of coal per hour was burned per square foot of firegrate, with a forced draught of about 6 inches of water pressure.

For ten years or so after the *Lightning* was built there was no great change in the design of machinery, but the size and power were increased, and, after having shown what could be done with these small craft, the same sort of practice was applied to much larger vessels. The locomotive boiler, which at first seemed satisfactory in boats, soon began to show its disabilities, and, while those fitted in torpedo boats gave a good deal of trouble due to leaky tubes, those fitted in larger vessels were bad failures.

In 1885 torpedo boats were fitted with water-tube boilers. The results were so successful that it was soon recognized that the locomotive boiler was no longer good enough for torpedo boats, and experiments were commenced in this country and on the Continent with different designs of water-tube boilers. Water-tube boilers had, of course, been tried for marine work long before, but had always failed from one cause or another. At the present day

it seems difficult to realize that it was impossible to get good solid-drawn tubes, and, while lap-welded tubes might be all right for a trial trip, they were found to corrode and lasted a very short time. To get over this difficulty brass and copper tubes were tried, but they did not prove satisfactory, and there was a return to steel. By degrees the tube makers learned to make good tubes, and, in a few years, water-tube boilers became the standard practice for all torpedo boats and similar craft. About 21 or 22 knots was the best speed which had been obtained with locomotive boilers; the introduction of the water-tube boiler at once increased it to 26 knots.

The troubles with locomotive boilers had not encouraged builders greatly to increase steam pressures, but, with the success of the water-tube boiler, pressures were at once put up and triple-expansion engines came into general use.

The first ships of the destroyer class that I have already mentioned were built in 1892; the *Daring* and *Decoy*, *Havock*, and *Hornet* were the first of them. They were vessels of about double the size and power of torpedo boats, had twin-screw machinery developing about 4000 H.P., with a nominal speed of 27 knots, but the best of them considerably more. The machinery was of the four-cylinder, triple-expansion type, with three or more water-tube boilers. It was during the development of designs of these boats, and of the 30-knot class which followed, that automatic feed regulation as we now know it was first successfully applied to marine boilers in this country.

I think if I read to you an extract from a paper read before the Royal United Service Institution in 1895, in which the engine and boiler-rooms of torpedo boats and destroyers were referred to, it will help you to realize the conditions then. Making a comparison between the attention which it was necessary to give the high-speed, highly stressed machinery in the torpedo boat with that of slow-running engines, the writer said: "Any want of adjustment in the engine can be detected by sound, by feeling, or by sight, and this is the order in which the senses are of importance for the engine driver. In the slow movement of the engine all the sounds can be identified, the motion is not so rapid as to prevent any part from being felt with but little danger to the skilful hand, and it can be seen at what part of the revolution any particular new noise takes place; in this way its cause may often be detected and a suitable remedy devised.

"If we turn from this comfortable-working heavy engine to the high-speed torpedo boat engine working at its highest power, we then note that the sound in the engine-room is confused by the addition of a number of auxiliary engines, each adding its own particular series of sounds to the now at least three cylinders of the main engine, and all these engines making a confusion which is further complicated by the fact that the auxiliary engines in their rate of working keep no constant ratio to each other or the main engines; they may be considered as part of an orchestra having a separate conductor for each instrument. Now take the next important sense for the engine driver feeling. The engines are revolving, say, 400 revolutions in a minute, and the important moving parts must be touched by the fingers, and any change of temperature detected promptly. If this is not done heating may ensue, which may oblige the engines to be stopped. In this rapid working the eye is even put to a great disadvantage. The motion is so rapid that no particular position of any working part can be assigned to it, while spray of water and oil is thrown in the eyes and the vision temporarily impaired.

"However, this description only applies to running at the highest speed, for when the speed is reduced to that used for ordinary cruising, the stresses on the parts are so small that the complicated machine has few parts which require special attention, and all comes under easy control.

"In the stokehold, also, there is a great contrast between full speed and cruising. The latter only involves the use of, perhaps, half the boilers, working so easily that the fires are dull and continue to do their work without any attention.

"At full power the firing scarcely ceases, and the forced draught gives such a high temperature in the furnaces as to render the light blinding and painful to the eyes, making the use of colored glass necessary to protect the eyes when examining the furnace to see in what part the fuel is most required. The space for stoking is limited, and the coal bunkers, being small, cannot afford convenient room for the coal being rapidly trimmed from them. The very large amount of air passing through the stokehold causes the coal dust to be carried about so as to be most unpleasant. In all this dust and hurry the water level and steam pressure must be attentively watched, and we owe much to our stokers for performing these duties, which are of the first importance for the speed and safety of the boat."

Shortly before the change over to turbines, torpedo boats were built with the main engines enclosed and fitted with forced lubrication. Had not the turbine arrived there can be little doubt that this would have been general practice, notwithstanding the increased weight and height which were required.

A great deal was learned about screw propeller design from the destroyer trials, and it was during these trials that the conditions governing what is now known as cavitation were clearly established.

By 1900 Sir Charles Parsons had proved the marine steam turbine a success. The Navy again wanted to get ahead of Continental rivals (this time the Germans) and it was decided by Lord Fisher's committee, which produced the *Dreadnought* design, to build larger and more powerful destroyers and utilize turbines instead of reciprocating engines. But this was not the only change. Oil fuel had been shown to possess so many advantages that it was to be used instead of coal. What was known as the *Tribal* class of destroyers were ordered with a guaranteed speed of 33 knots and a nominal horsepower of 15,000. The *Tartar*, the fastest of them, did over 35 knots. The turbines proved a complete success, but, without oil fuel, this performance could not have been obtained, no matter what the type of boiler. A forced-draught stokehold burning coal could only be run successfully with a highly trained crew, and then only with the best coal. When burned at the rate of 70 pounds to 80 pounds per square foot of grate, it was not possible to continue for more than about three hours without the bars becoming clinkered up. With oil firing, not only can steam be maintained as long as the fuel lasts, but one man can do the work of half a dozen and the stokehold is quite clean and comfortable.

Shortly before 1914 the economies due to superheat on land turbines had been found to be so great that boilers were fitted with superheaters in some of the destroyers. It is obviously more difficult to arrange for superheat in a marine turbine, which has occasionally to be reversed by introducing steam quite suddenly at its cold end, than in a turbine which always runs in the same direction, and can be slowly warmed up, as is the case with turbines on shore. The necessity for building boats quickly and avoiding unnecessary risks during the war period, put an end for the time to further developments with superheat.

In 1925 the British Admiralty ordered two experimental destroyers, both of which had boilers with superheaters. The larger of them, the *Amazon*, was about the same size as the vessels built since, and her auxiliaries were practically all turbine-driven. The power was about 40,000 H.P., and the steam was generated by three boilers. You will see that the boiler units had

increased very much in size. They have been increased even more latterly, and powers as great as 40,000 H.P. are being developed by only two boilers. Reducing the number, of course, greatly simplifies the piping arrangements, etc.

The late Sir Charles Parsons advocated higher pressures and superheat, believing that it should be possible to obtain as high an efficiency with turbine machinery as with internal combustion engines, and in 1928 the *Acheron* was built to work at 500 pounds per square inch pressure and 730 degrees F. total temperature. The result obtained showed what could be done and the experiment resulted in pressures being increased, though not to quite such an extent.

I mentioned that Sir Charles Parsons considered it should be possible for turbine machinery to compete with internal combustion engines in economy. It may be asked why no attempt was made to fit a torpedo boat or destroyer with internal combustion engines. The answer is that they cannot be made light enough. Internal combustion engines of considerable power have been employed in submarines for a long time, but they are much too heavy to drive a surface torpedo boat. The lightest that were used during the war period gave only about 20 H.P. per ton, whereas steam turbine machinery gave 60 H.P.

By the use of supercharging and higher speeds of revolution, engines developing up to 1000 H.P. or 1500 H.P. are being built which are considerably lighter, but there seems no prospect of any internal combustion engine being available which can compete with turbine machinery where tens of thousands of horsepower are required with the light weight which is necessary in vessels of the destroyer class.

COASTAL MOTOR BOATS.

I have described how the small torpedo boat by 1914 had developed to a size about 1000 tons, and become a powerful and expensive unit. During the early stages of the war there would have been opportunities for torpedo attack if it had not been that mine fields prevented vessels of the size of destroyers getting to the objective. Hence it was natural that naval officers should desire some light-draught small torpedo boat which would be able to go over the mine fields.

Since the early days of the steam torpedo boat, the light petrol engine had enabled launches to be built of more than double the speed, and small motor torpedo boats had actually been experimented with. It was decided to build the smallest possible boats that could take an 18-inch torpedo, carry them in the davits of light cruisers, and put them in the water where an attack was required.

The first of these boats having proved successful, larger ones, 55 feet in length, to take two torpedoes, were built. I should like to mention that when ordered, they were called motor torpedo boats, but it was considered undesirable that it should be generally known that such things existed, so the name coastal motor boats was given to them. Carrying a load of rather over 2 tons of torpedoes and other ammunition, and developing a speed of about 40 knots, they were a very great advance on anything of the sort which had been built before. Towards the end of the war a limited number of even larger boats, 70 feet in length, carrying a load of 5 tons of torpedoes or mines, were built.

There is no time to go into the design of these boats in any detail, but I would explain that their high speed depended not only on their light machinery (consisting of specially designed twelve-cylinder "V" type engines very similar to some types used in aeroplanes, but having special features suit-

able for work in boats, and not running at such a high rating), but also on the fact that the power-weight ratio of a loaded boat was sufficient to enable her to be driven on to the surface of the water, thus avoiding the ordinary wave formation which absorbs so much of the power in driving a ship in the ordinary way.

I should like to refer again to the hull design of the small motor torpedo boat. I have mentioned that the power-weight ratio is sufficient to drive the boat forward in a skimming condition. The first man to suggest this was the Rev. Mr. Ramus, in the early 'seventies. My father worked at the same idea in his early days, and he actually made alternative designs for the *Lightning's* hull, with the intention of making her skim if possible. He recognized, however, that he could not get machinery light enough at the time. When it was available, he returned to the problem again, and, as a result of experiments with models and actual boats, he produced in 1909 or 1910 a form of hull that would skim and had good sea-going qualities as well. It was by slightly modifying this design to make it suitable to carry torpedoes in the stern that the motor torpedo boats were successfully produced during the war period.

This form of hull, which had what is now sometimes called a "hard chine" bow, combined with a break or step in the lines about the middle of the boat, is now universally adopted where the highest possible speeds are desired, but it should be made perfectly clear that the skimming or planing principle can only be applied to boats of moderate dimensions. As far as boats are concerned, the laws of similitude, and the speeds at which boats of different dimensions will skim, are definitely established.

What is now called a 16-foot planing dinghy will reach a skimming speed when she is driving at about 17 knots, and requires a motor developing about 50 H.P. to do this. A 50-foot motor torpedo boat will begin to lift and skim at about 30 knots, but if a 300-foot destroyer, with a similar form of hull, could be equipped with enough power to make her skim, the effect would not take place until she attained a speed of about 70 knots. The power which would be required would be at least 200,000 H.P., five or six times as much as has ever been found possible to put in a boat of these dimensions. I have stressed this point because it appears there are a good many people who have imagined that the skimming principle will be applied to larger craft.

THE FUTURE.

We have seen that the motor torpedo boat is a much more potent weapon than the early steamboats were, and with the knowledge that a dozen or so of the smaller navies, as well as some of the larger ones, have adopted them, it must be assumed that they are of some value, at any rate as one of the pawns in the war game.

Engineers and ship designers are always at work to meet the demands of naval officers whose business it is to go one better than the vessels of the navies that they may have to oppose, and may perhaps be forgiven for speculating as to the extent to which history will repeat itself.

Will larger and faster motor boats be built, as in the case of the old steam torpedo boats and destroyers, or have the power of the small-caliber machine gun and modern developments of fire control changed things so much that, with the additional aid of the aeroplane, there is an effective answer? To the lay mind it would appear that there must always be a great difference between operations in protected water (*i.e.*, protected as regards weather conditions) and the open sea.

As major actions, and even attacks on merchant shipping, generally take place in the open seas, it would seem that the tendency must be for boats (on which the crews are expected to live) to become considerably larger, and that the larger motor torpedo boat or the motor torpedo-boat destroyer (if she is ever built) will have to approach the size of the last steam torpedo boats in the British Navy, if it is to be effective in average weather conditions. But it will not be easy to build such craft with anything like such a high smooth-water speed as the light motor torpedo boats.

Past experience has shown that each class of warship tends to become larger and more heavily armed, until it is wrongly named, if the original designation is retained. It is evident that the attempt to limit the size and armament, by agreement between different countries, has failed. The present-day torpedo boat, which is the destroyer, was to be limited to 1850 tons, but some navies possess what they call destroyers, of very much greater size, which would not long ago have been called Third Class Cruisers.

Now that international limitations of size and quality are at an end, how will the mechanical engineer be affected? Apart from the propelling machinery, ships at the present day are so filled up with mechanism and appliances produced by engineers, and necessarily operated by skilled mechanicians, that it is difficult to imagine how any more can be put into them. But new and more complicated apparatus is constantly being designed, and not only are the new classes equipped with it, but older ones have to be adapted to take it. It is for those who will command the ships to call for everything that they believe will enable them to employ the ships most successfully, but an engineer cannot help appreciating that the more complicated the apparatus becomes, the greater the chance of its being put out of action, and the longer the time required to train men to look after it.

It is much easier to add complication than to simplify, but it seems to me to be all-important to endeavor to simplify. In theory it may be possible to have the most perfect piece of apparatus which would always enable a captain to get his blow in first, but in reality there may be such difficulties in producing it that he does not get the opportunity, and so I suggest that the work of mechanical engineers will necessarily be in the direction of simplification.

Simplification and reliability go together. The most ingenious devices cannot be of real benefit unless they are reliable. Those who served through the war say that the strain of having ready for work at four hours' notice, for 4½ years, the less complicated apparatus and mechanism which existed then, was more than many men could stand.

In any case, it is manifest that the work done by mechanical engineers and those they direct is of increasing importance in preparing for the country's safety as well as its economic position, and I feel sure that every member of the Institution recognizing this is only too anxious to play his pa t.

"MONSTROUSLY INGENIOUS."

Sir John Thornycroft concluded his Presidential Address to the Institution of Mechanical Engineers on Friday, October 22nd, with a plea for simplicity in mechanical design. "It is," he said, "much easier to add complication than to simplify, but it seems to me to be all-important to endeavor to simplify. . . . Simplification and reliability go together. The most ingenious devices cannot be of real benefit unless they are reliable." May we remind our readers that over eighty years ago another famous engineer and shipbuilder, Scott Russell, speaking to the Society of Arts, asked his audience—

"Were they not struck with the fact that nearly all the inventions they now heard of no more seemed monstrously ingenious, whilst the inventions actually in use were those which appeared to have got rid of all the ingenuity and to have merely retained one or two plain, simple, common-sense elements in them?"

It would be difficult to find any mechanical engineering product in which reliability is more essential than the equipment of war ships. In passenger and commercial ships a breakdown ordinarily causes only delay, but no fatal consequences; in a warship on hostile duty a failure may have far-reaching consequences—the loss of the ship to the enemy, if not the loss of an action. Hence, particularly during war, every class of naval vessel, whilst in commission, must be trustworthy in every part, ready for action at short notice, and in such a condition that every single item of the complex mechanism which it contains may be trusted to perform its duties without hitch or delay and without giving anxiety to those in command. It is not difficult to believe that the strain which is put upon the responsible personnel ashore and afloat is enormous. "Those who served through the war," said Sir John, "say that the strain of having ready for work at four hours' notice, for 4½ years, the less complicated apparatus and mechanism which existed then, was more than many men could stand." Nevertheless, the multiplication of complexity still goes on. Since the war it has increased greatly and there is no sign yet that it is coming to an end. To complicate is easier than to simplify, but perhaps some day there will arise a designer who has the ability and the courage to delete everything of which the value does not outweigh the disadvantages and even to set the merits of simplicity and resulting trustworthiness against some loss of efficiency or convenience. It would be of the highest technical interest if a small committee of experts would examine, let us say, a destroyer, and estimate the relative value of every item it contains. There is, we believe, a good deal of duplication and even triplication resulting from the fact that independent drawing-offices prepare designs for their own equipment. It is at least conceivable that unification could be effected in some of these cases. Sir John implied, if he did not say so in as many words, that there was greater complexity in recent destroyers than could be justified by real necessitv. A committee which resolutely determined not to be swayed by personal predilections would, we imagine, find it not insurpassably difficult to indicate what parts of this increased complexity might be surrendered, and what part was an ineradicable concomitant of the advances in practice—higher pressure, anti-submarine and anti-aircraft equipment, range anticipating, range finding and so on—which have been introduced in the last twenty years. We have mentioned "personal predilections" because we assume that in the design of warship machinery, as in that of commercial ships and land plants, it plays a not negligible part. On the one hand may be found men who believe in the greatest automaticity and refuse to see that complexity increases liability to breakdown, and on the other, men who are resolute in their belief that after all is said and done, the human machine is, of all machines, the most to be trusted in emergency. There is in all classes of mechanical engineering a tendency for the former to carry the day. That is a great compliment to mechanical engineers, but engineers themselves know, to quote Sir John once more, "that the more complicated the apparatus becomes, the greater the chance of its being put out of action, and the longer the time required to train men to look after it."

It cannot be expected that a warship will ever again be simple. Each new invention brings with it new equipment which has to be fitted within the limits of the hull. But when an author of great experience of a particular class of war vessels urges the desirability of greater simplicity it is manifest

that he has in his mind the direction in which simplification should be sought. We are not in his secret, in that matter, but we are perhaps not far wrong in assuming that foreign craft are, in general, more subject to criticism for excessive complexity than those of the British Navy. In this country the simplicity of machinery has always commanded respect. On the contrary, many foreign nations rejoice in complex machinery and are prone to value "plain, simple, common-sense elements" less highly than we do. Partly because there are always lots of people who insist that we should follow the example of others and partly because foreign orders have an inevitable effect upon design, we have had in all branches of engineering to surrender some of our national liking for simplicity. In warships we produce masterpieces of engineering, for nothing less than masterpieces will do. Since every single item, down to the least, must be above suspicion, the standards insisted upon in the specifications are the highest conceivable. But it is well to remember that in action this excellence is of very brief value. Its purpose is to enable a ship to get its blow in first. We protect it as well as we can behind steel walls, but if the enemy succeeds in striking before we can, even if he does not touch a vital element, he may throw out of gear a whole train of mechanism and devices and compel a return to simpler methods of operation. "In theory," said Sir John, "it may be possible to have the most perfect piece of apparatus which would always enable a captain to get his blow in first, but in reality there may be such difficulties in producing it that he does not get the opportunity, and so I suggest that the work of engineers will necessarily be in the direction of simplification."

TORCH-HARDENING OF GEAR TEETH.

At a recent meeting of the American Gear Manufacturers Association, Mr. W. E. Sykes of the Farrel-Birmingham Company, Inc., of Buffalo, N. Y., presented a paper of which the following is an abstract from the November, 1937, issue of Machinery. An ingenious and successful method combining the use of an oxy-acetylene flame followed by a quick quenching with an attached water jet is described.

The technique of hardening gears below, say, 12 inches in diameter has been well developed, but the hardening of larger gears has presented some difficulties. Some of these larger gears are furnace-heated and afterward quenched; others are carburized and quenched. The application of larger gears so hardened is, however, confined to somewhat low speeds, due to the fact that it is impracticable to limit the distortion to a very small amount.

For a long time there has been a need for a method of hardening the teeth of large gears without appreciable distortion. When the nitriding process was introduced about twenty years ago, it was thought that it would be useful for large gears; but it has not proved as universally applicable as was expected. The nitriding process is slow and expensive when applied to large gears, and the depth of hardness is not so great as desired. Moreover, the surface hardness resulting from the nitriding process is so great that it tends to make the metal brittle.

Recently, considerable progress has been made in the hardening of gear teeth by means of an oxy-acetylene flame, followed by a quick quench. This idea is not new; it was practiced twenty years ago, but made litfle headway until the introduction—some seven or eight years ago—of a machine that could guide mechanically a suitable torch fitted with a water jet. This

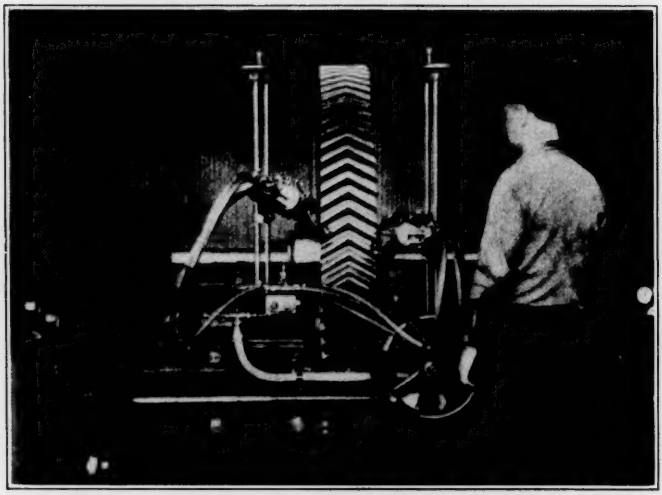


FIGURE 1.—TORCH-HARDENING EQUIPMENT READY TO BE APPLIED TO A HERRINGBONE GEAR.

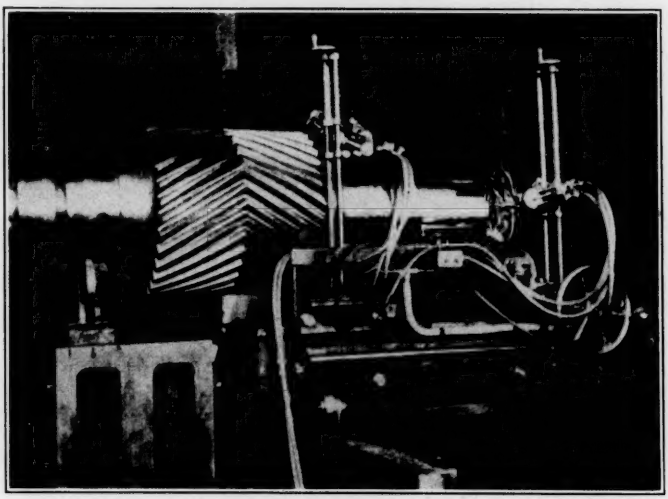


FIGURE 2.—TORCH-HARDENING EQUIPMENT USED FOR HARDENING SPLINES AT THE END OF A SHAFT.

development was pioneered in England by A. E. Shorter, and the method has since been adopted in the United States.

The process has the appearance of being remarkably simple, which has perhaps been its greatest disadvantage, as it has commonly been assumed that it is a simple matter to devise a mechanical method for guiding a torch with an attached water jet. The haphazard way in which the operation has been carried out, however, has often caused disappointing results, and, in consequence, torch-hardening has been thought an unsuccessful process.

It is thoroughly recognized that, in using a carburizing process or any other hardening method, a suitable steel must be employed. In view of this, it is strange that many experienced engineers should have expected the torch-hardening process to operate successfully with almost any kind of material. It is obvious that the application of a torch to poor steel will not eliminate impurities and other defects. A poor material torch-hardened—or hardened in any other way—may give less satisfactory results in service than if it were unhardened. It is easy with the torch-hardening method to ruin an otherwise good gear; and it is also easy to make a poor gear into a hopelessly bad one.

In considering the torch-hardening process, one should bear in mind that by its use steel is heated to a rather high temperature and rapidly quenched; hence a steel suitable for this treatment should be used. Present experience indicates that a non-alloy steel containing from 0.4 to 0.6 per cent carbon is suitable. Some of the alloy steels have also given good results, but greater care is necessary in applying the correct heat and also in applying the quenching fluid at a correct distance from the heating flame. Steel castings containing as low as 0.3 per cent carbon, with a high percentage of manganese, have been hardened satisfactorily.

One of the difficulties in using the process is to gauge the temperature of the heated metal. The author knows of no really satisfactory pyrometer or other temperature-measuring instrument that is applicable to the torch-hardening method. Furthermore, it seems that the only method of ascertaining the hardness of the gear tooth correctly is by removing it from the gear, which, of course, is impracticable except for experimental purposes. None of the available hardness-testing instruments are adapted for application to the surface between two gear teeth.

However, even though we cannot measure the temperature or the hardness, but still get good results from the gears, there is no reason to question the value of the process. In nearly all developments, the method or machine has come first and the instruments for measurements and inspection later.

THE FARREL-BIRMINGHAM TORCH-HARDENING MACHINE.

A torch-hardening machine developed by the Farrel-Birmingham Co. was illustrated and described in June, 1937, Machinery, page 687. Other applications of this machine are shown in the accompanying illustrations, Figures 1 and 2. This machine has been especially developed for hardening gears with parallel axes. No attempt has been made to apply it to the hardening of worm-gears or bevel gears. However, a machine for hardening bevel gears has been developed by the Gleason Works.

Figure 1 shows the torch or heating equipment. There are two torch heads, each of which carries two jets for the mixture of oxygen and acetylene. Each jet impinges on one side of the gear tooth, with the result that when herringbone gears are being hardened, four jets are in simultaneous operation; thus the right-hand helix of one tooth and the left-hand helix of another tooth are hardened simultaneously. When single helical gears are

hardened, one pair of jets only may be used; or two pairs may be used, one pair working on one gear and the other on a second gear, the two gears being ganged on one arbor. A similar method can be used for hardening straight teeth or splines. In Figure 2, for example, the splines at the end of a shaft are being hardened.

The torch heads are provided with mechanisms for making suitable adjustments for correctly positioning the flame jets and the water jets. These adjustments are very important. The water supply is carried in a tank which forms part of the base of the machine and is brought to the water nozzles, located behind the flame nozzles, by a motor-driven pump. The temperature of the water is controlled by having a constant supply running into the tank from the water main while a constant amount is drained from the other end of the tank. A constant water pressure is necessary; direct connection of the water nozzles to city water mains has proved troublesome because of variable water pressure.

When helical or herringbone gears are being hardened, it is necessary to rotate the gear in unison with the movement of the torches. This is accomplished by means of a pin guide fixed to the traverse saddle of the machine which engages the teeth of the gear. This pin is also used as an indexing device.

Up to the present, this machine has been found suitable for hardening teeth from 1 to 4 diametral pitch. It has been used for pitches as fine as 6 diametral pitch, but it is not so satisfactory for the fine pitches as for relatively coarse pitches. It is believed that it is practicable to harden as fine as 8 diametral pitch teeth; but when the pitches are so fine, the depth of hardness needs to be very precisely controlled, and the work is tedious and slow. It can be readily seen that to harden 100 teeth of 6 diametral pitch takes nearly as long as to harden 100 teeth of 1 diametral pitch, and there is less to show for the labor and expense involved when fine-pitch teeth are being hardened. Fine-pitch gears, however, are usually of small diameter and can be more satisfactorily hardened by other methods.

It has been necessary to ascertain by experiments the correct gas pressures and flames for different pitches and different materials. These data are now in tabulated form, so that an operator can work to a chart, thus obtaining uniform and satisfactory results.

HARDNESS OBTAINED BY THE NEW PROCESS.

One question often asked is: "What is the hardness obtained?" It has been found that it is possible to obtain any hardness between 60 and 80 scleroscope, or 400 to 550 Brinell. Experience shows, however, that it is not desirable to obtain a hardness greater than 75 scleroscope. In fact, it may be that a hardness of about 70 scleroscope is better. It is not known with certainty whether a very hard surface on any gear tooth is desirable. The depth of hardness is, of course, important; but it is more important that the hardness decrease gradually from the surface of the tooth toward the core or center. A very sharp line of demarcation between the hardened portion and the soft portion should be guarded against. It is easy to get this undesirable result by heating the metal too hot and quenching it too quickly.

The question of the desirability of preheating and of drawing has been raised. The author has not found that either of these operations is necessary or desirable. Preheating, if desired, can easily be done without any appreciable extra expense, and a drawing operation can be carried out on the machine without great trouble; but it is believed that the latter operation, at least, would be detrimental.

RESULTS OBTAINED WITH TORCH-HARDENED GEARS.

Some of the results obtained with torch-hardened gears in operation may be of interest. Up to the present time, there are approximately 700 pairs of gears that have been hardened on the machine described. These have given excellent results, with the exception of one pair, which showed some spalling near the ends of the teeth. However, it was found that this pair of gears was not mounted in true alignment. It was not possible to determine whether the undesirable effect was due to the torch-hardening or to the mounting of the gears. There are many sets in operation that have replaced similar gears unhardened; those torch-hardened have shown greatly increased life and are so far running satisfactorily without discernible wear.

It has been stated that torch-hardened gears will carry twice the load of unhardened ones. While it is probably true that a properly torch-hardened gear made of the correct material will carry at least twice the load of a gear made of the same material unhardened, it is by no means true that *any* torch-hardened gear will carry the same load as a gear of the same size made of a better material, unhardened.

Another mistake that many have made is to assume that because a gear is torch-hardened, it will stand great abuse and that it is not necessary to mount or lubricate it properly. A torch-hardened gear with only a 30 per cent bearing surface on the teeth cannot be expected to be better than an unhardened gear with a 100 per cent bearing surface. It may be less satisfactory than an unhardened gear; for if an unhardened gear is mounted out of alignment, it will more quickly wear to a reasonably large surface contact than a hardened one. Torch-hardening, or any other kind of hardening, will not eliminate faults in machining and mounting, and no hardening process will make bad steel into good steel.

It will be readily recognized that torch-hardening is not limited to gear teeth. It has already been used successfully in hardening many other machine parts. In the future, it is probable that every well-equipped hardening shop will have facilities for torch-hardening. At the present time, this process is being applied abroad successfully for hardening automobile engine crankshafts, cams, and many other machine parts.

SHIP PROPULSION BY THE EMMET MERCURY VAPOR PROCESS.

The use of the mercury vapor cycle in power generation has hitherto been largely associated with experimental power plants ashore. In the following paper presented by Mr. William L. R. Emmet at the annual meeting of the Society of Naval Architects and Marine Engineers, New York, November 18 and 19, he discusses the possibilities of utilizing the mercury vapor process for ship propulsion, with a large estimated reduction in fuel consumption. The abstract reproduced herewith appeared in Shipbuilding and Shipping Record, London, England, November 25, 1937.

The purpose of this paper is to make public for the first time certain new knowledge relating to the mercury-vapor process invented by the writer years ago. This knowledge may have application to many possible uses of this process, but it is to uses with oil fuel, as in ships, where the experimental development is considered complete and final, and it is to applications of the process to ships that this paper is confined.

After long and extensive experimentation this process has been applied to commercial use in three large plants. The first of these is at Hartford, Conn., where the exhaust of a 10,000-Kw. mercury turbine makes steam for use in a large electric power station. The other two plants, the capacities of each of which are intended to be about twice that of Hartford, are situated at Kearny, N. J., and at Schenectady.

The Hartford plant has been in operation for about eight years. The tubes in the boiler were changed once on account of a detail which was found to be undesirable, and there have been about three stoppages to clean the boiler, a rather elaborate process in this type of boiler. For the rest of this time the operation has been practically continuous at or near full load. The left side of Figure 2 shows an elevation of this installation.

HIGH PRESSURES.

Since the mercury process began to be worked on, the art of making power with steam has greatly advanced. Pressures of 1400 pounds per square inch and over have been used, and temperatures as high as 1000 degrees F. These changes have brought large reductions of fuel consumptions, and, through improved metals and other means, many of the supposed difficulties have been largely overcome.

These successes with improved steam methods have led many people to conclude that the need for anything so different as the mercury process has passed. The writer, however, has long known that, if a really good mercury boiler could be found, no application of steam could possibly compete.

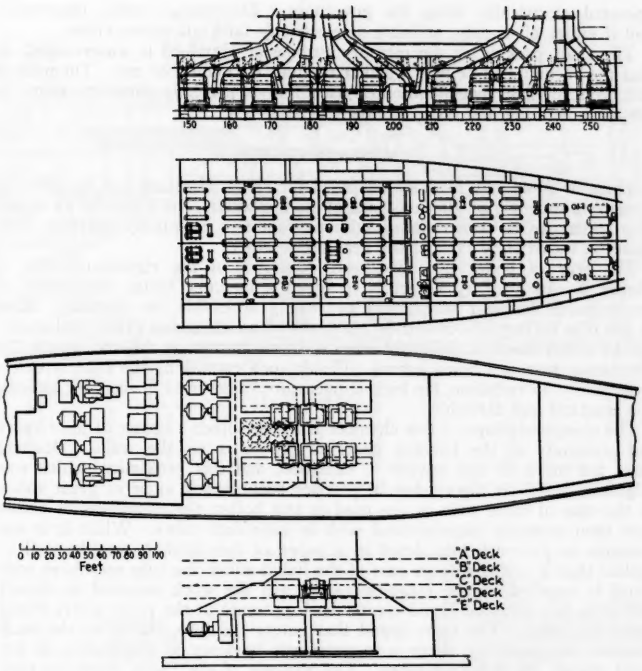
Extreme steam conditions, such as are mentioned above, have been applied only in one or two ships, and the degrees of operating success are unknown to the writer, although the fuel rates accomplished have been made public. The best of these fuel rates apply to a German electrically-driven ship which used 1200 pounds per square inch steam pressure and a steam temperature of 877 degrees F. These are quite extreme conditions, but the fuel rate reported is only 5 per cent lower than the conservatively estimated performance of the *Normandie* at 130,000 S.H.P., which has been taken as an example for comparison in this paper.

Since we calculate that the mercury drive, with very conservative pressures, would better the *Normandie* by 38 per cent, it would appear that there is still margin for the mercury.

The Hartford mercury plant operates with a maximum steam temperature of about 700 degrees F. and a maximum mercury pressure of about 65 pounds. The steam conditions are far from ideal, and yet the plant gives a fuel economy far better than any steam plant in existence.

The fundamental need in the mercury process is a good mercury boiler; given that, the whole has an ideal simplicity and practical fitness. Mercury has ideal thermo-dynamic characteristics, and the steam-making parts have a simplicity and safety which give the process peculiar fitness to ships where steam-making is the big job.

This paper shows and explains a kind of boiler which is not a mere illustration of a type, but an actual unit now in operation, which, in any needed number, can be successfully used to produce any desired quantity of power. Its fitness is being demonstrated at Pittsfield, where one such unit is in operation in regular service. Its adaptability to different uses is illustrated in this paper by the case of the *Normandie*, where it might be desirable to install 72 such units, and by the case of a 3000-H.P. geared-turbine tanker which could be run by one.



Mercury boiler layout in the "Normandie" compared with present installation

FIGURE 1.

The principles and conditions involved in this boiler might be applied to boilers of a wide variety of sizes and shapes without departing from the relative ratios of load to furnace volume or radiant-heat absorbing surface. In such a large ship as is here illustrated it would, presumably, be desirable to use a much smaller number of boiler units than is shown, and this might safely be done with very little additional experimentation. This paper simply shows what could be done with just such boiler units as that which is now being run at Pittsfield.

Before describing and explaining this new type of boiler, it may be well to explain that a view of the plant at Hartford is given because this plant has operated for years without trouble except in the boiler, as has been explained. Exactly similar devices could be used on any ship with certainty of equal success, the boiler alone as proposed for ships being different from that at Hartford.

The governing at Hartford is actuated by air pressure, centrifugally produced in the generator. The governing valves are moved hydraulically by oil cylinders. They are forced open against springs and the oil valves are

operated electrically from the governors. Everything works negatively; and if either oil supply, pressure or electricity fails, all valves close.

The shaft packing of the mercury turbine at Hartford is water-sealed, so that the vacuum can be held whether the unit is running or not. The method has been running successfully for years and is perfectly suited to ships, as are the governing and other auxiliary details.

MARINE APPLICATION.

Thus, of these new methods proposed for ships, Hartford can be taken as a running example of all parts outside of the boiler. In Pittsfield an actual ship boiler can be seen running, with no condition essentially different from those on board ship, even in the heaviest weather.

The type of boiler here discussed is shown in the right-hand side of Figure 2. Its primary object is to make a mercury boiler with tubes of ample inside diameter which will be readily accessible for cleaning. Most of the tube surface is exposed on the walls of an elongated cylindrical chamber to which flame is delivered from a single burner at the end where the circulating mercury liquid enters. Under such conditions the heat is delivered mainly by radiation, the high-temperature range used in mercury making this practical and desirable.

The elongated shape of this chamber has two objects: saving of floor space and proximity of the burning gases to the tubes on the walls. Burning gases are more or less opaque to radiation, and this proximity, which was originally based on theory, has in practice been proved to be of great value. In the case of tubes such as are used in this boiler, the conditions of action have been carefully experimented with in individual tubes. While it is not desirable to go much into detail in a paper of this kind, it may be well to explain that in action a large part of the liquid which the tube may have contained is expelled by the escaping vapor, and the work required to impart motion to this escaping liquid creates back pressure at the point where liquid enters the tubes. The more liquid that enters the tube, the more the back pressure; consequently, there is an automatic tendency to distribution of the liquid among the different tubes. The passage of the liquid from the tube may be likened to the discharge of shot from a gun.

The conditions in this boiler are, therefore, such that only the mercury actually moving in the tubes is in use; the excess will be in the down-run chambers and since wide variations of level in these chambers are permissible, the type is well adapted to use in groups either on shore or at sea where motion affects levels.

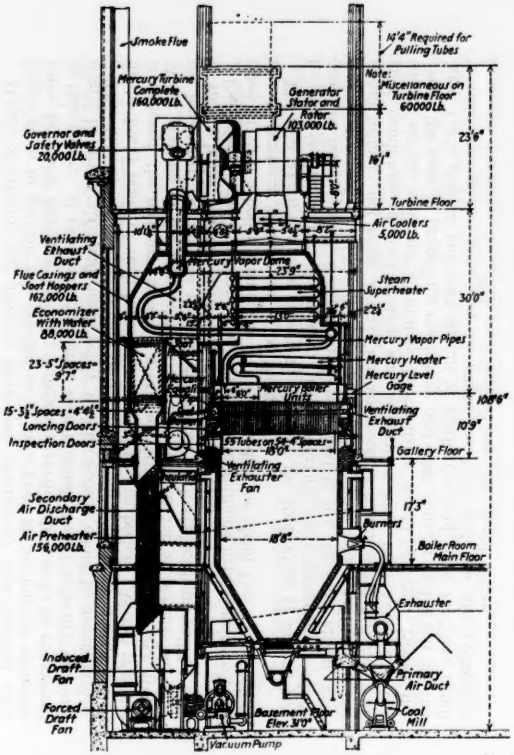
There is one very important condition in mercury boilers which should be explained here, namely, the fact that hot mercury slowly dissolves and washes away the surface of iron, more with some iron alloys than with others, but always to an appreciable extent. This fact has been known only for about five years, and constitutes the most important reason for the need of boilers of the type here described. The rate of such washing away increases with the pressure and consequent temperature used.

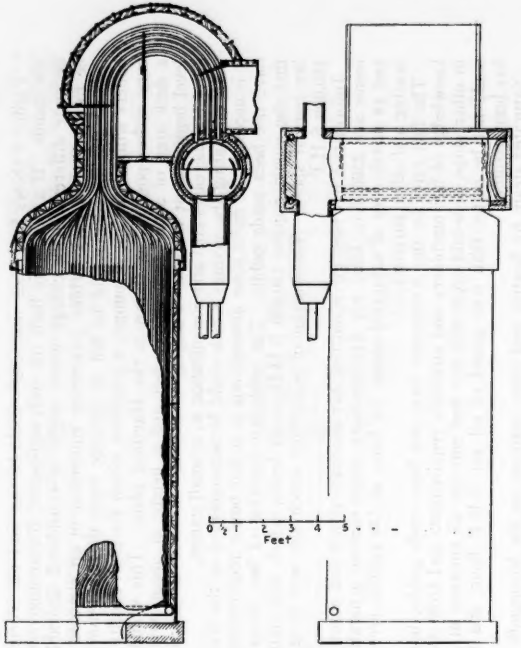
TROUBLE FROM DIRT.

With such mercury pressures as have been used, the rate of washing has been very slow, and in such a boiler as is shown here, would involve small expense for tube maintenance. The serious troubles in other mercury boilers have come mainly from the dirt which this dissolution has put into the mercury, which in small inaccessible passages can cause stoppages. In a boiler of the type here shown, such danger is entirely absent.

FIGURE 2.

NOTES.





Left: Sectional elevation of mercury boiler plant at Hartford, Conn., U.S.A.

Right: Marine type of mercury boiler.

FIGURE 2.

Means of alloying the mercury have been extensively experimented with, which seem to prevent this dissolution of iron even at the highest temperatures, but these have not yet been sufficiently verified by use to be considered in this paper. If experience justifies such method, higher mercury pressure would be practicable and much better fuel economies could be accomplished.

This dissolution of iron occurs only in the hottest parts of tubes, that is, in the lower parts of such tubes as are used in this boiler. As the pressure is relieved, the mercury tends to give back iron rather than to take it up. When wasting of the iron-tube surface has gone as far as permissible, only the lower part of the tube need be replaced. Such replacement will be easy in such a boiler without removing it from its setting.

Experience would indicate that, under the conditions here considered, the tubes of such a boiler would run 24 hours a day for about four years before any replacement would need to be thought of.

The case which has been chosen to illustrate the application of this process to ships is that of the *Normandie*. In considering the improvements which could be accomplished, it has been thought best to use the same steam pressure and superheat which she now has. The quality and conditions in her steam turbines not being exactly known, good standard steam turbines with good conditions of feed heating and auxiliaries have been assumed. The weight saving, while not accurately determinable, would be large. Something over 1700 tons in propelling machinery and 3300 tons in fuel when leaving New York, plus an unknown weight of auxiliaries and stack facilities, could be taken out of the ship. No allowance has been made for any reductions in power requirements which such weight removal might afford.

GRAVITY FEED.

Figure 1 shows how such machinery could be put into the *Normandie* as she stands. If a ship were built for such equipment, the arrangement might be quite different. One change which might be considered desirable would be to put the mercury-turbine generating equipment in an elevated position so that the mercury would be fed by gravity from the condensers to the boilers without the use of pumps, a condition which the high density of mercury makes possible, as shown in the Hartford plant. This would require a deck area of about 6000 square feet and a height of about 20 feet at a level beginning at C deck. Pumping of mercury involves no practical difficulty but increases cost and complication to a small extent.

In estimating the savings which could be accomplished on the *Normandie*, it is necessary to make some assumptions as to her power requirements which have not been made public. The published intention of her designers was that she would require 130,000 S.H.P. at 28 knots, which was stated to be her normal speed. The maximum power for which she was designed was 160,000 S.H.P.

Information has been given out that her auxiliary power and steam requirements are 2500 Kw. from her five auxiliary steam-turbine generating units and 18 metric tons of saturated steam per hour, at 150 pounds pressure, for heating and other purposes.

The fuel rates on the *Normandie* have not been made public, but from a knowledge of her machinery and auxiliary requirements and from experience in other ships, it would seem that her fuel rate for all purposes at 28 knots could not be better than 0.69 pound of oil per S.H.P.-hour, and this rate has been assumed.

Saturated steam for heating and other purposes on the *Normandie* is made in four Scotch boilers, but with the mercury process it is not desirable to do

this. In this process any steam making results in a large production of power from mercury turbines, so that it becomes desirable to get this heating steam by bleeding either the main or the auxiliary steam turbines. Such method is considered in the estimated comparison.

Under such conditions it is calculated that the *Normandie*, using 130,000 S.H.P., with the steam conditions now used and with mercury vapor at 115 pounds absolute at the turbine would require for all purposes about 0.42 pound of fuel oil per S.H.P.-hour.

SAVING IN FUEL.

Thus, if the *Normandie* were equipped with mercury drive under the conditions stated, something like 38 per cent of all the fuel she uses would be saved.

The average power which she actually uses or the amount of fuel that she burns per year are not known to the writer, but if she averaged 130,000 S.H.P. and 28 knots and made 20 round trips per year between New York and Cherbourg, the saving in fuel cost at present oil prices would be over $400,000 per year.

In addition to the saving in fuel there would be a very large space saving—about 400,000 cubic feet—not including the less space required by stack and blower facilities.

The logical use of such fuel economies as this process affords would in most cases be to make higher speeds commercially desirable and to modify models and conditions to suit. That is to save time rather than fuel.

The question is often asked: "Where is the great quantity of mercury required for large uses of this process to come from?" With boilers of the type here shown, something like 3 pounds per S.H.P. will be required. Extensive investigations have shown that there is no possibility of a mercury famine or of any permanent large rise in the price. Experience has shown that the loss of mercury will always be negligible. There can be no danger from mercury poisoning, since all mercury-carrying parts are in enclosures which are kept at a negative pressure by stack or blower suction.

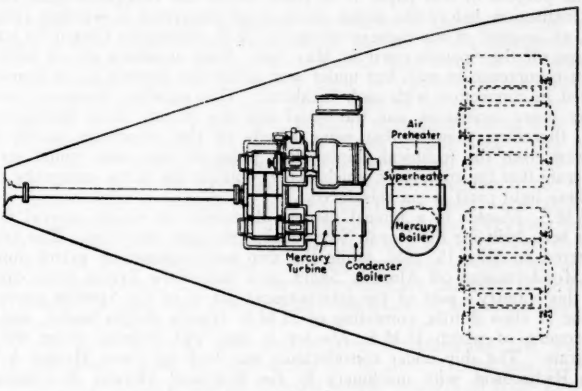


FIGURE 3.—MERCURY BOILER ARRANGEMENT IN TANKER.

Costs of new constructions are always difficult to get, and no attempt has been made to get detailed estimates in the case here discussed. The materials of which the boilers, superheaters, air heaters, etc., are made are similar to those used in steamers. The mercury turbines are simpler than steam turbines, and the mercury condensers are simple in construction. The fact that about 2000 tons in the weight of such parts is saved indicates that, on any proper manufacturing basis, the cost of mercury required would be much more than offset by a less cost of machinery.

The efficiency of mercury turbines is generally less impaired by reduction in size and power than is that of steam turbines. With mercury, the rate of improvement over a steamer will generally be greater than in such ships as the *Normandie*.

In many cases existing steamers could readily be converted into mercury-driven ships. Figure 3, which shows the geared mercury drive for a 3000-H.P. tanker, is an example of such a case.

One condition which makes the mercury process peculiarly practical for ships is the extreme simplicity of the making of steam by the condensation of the mercury vapor. The surface required is small and can be made readily accessible for cleaning.

The temperature differences involved will generally not exceed 20 degrees F., so that no trouble or maintenance expense are to be expected, even if the worst water is used.

DAMAGE TO H.M.S. *HUNTER*.

The extent of the damage sustained by H.M.S. *Hunter* in striking a mine off the Spanish coast is described by H. Stanley in a paper read before the Institution of Engineers and Shipbuilders in Scotland and appearing in volume 81, part 2, of the December, 1937, edition of the transactions of the society. Due to space limitations only a selected few of the author's many photographs and diagrams have been reproduced.

The purpose of this paper is to place before the Institution and, through the Institution, before the wider circle of all interested in warship construction, an account of the damage to one of H.M. destroyers caused by striking a mine off the Spanish coast in May last. Such accidents are of fairly frequent occurrence in war, but under war conditions secrecy is, of course, observed in connection with such incidents. This accident, however, occurred under peace conditions, and the vessel was one of our latest destroyers. It was, therefore, thought that some details of the occurrence would be of interest from the technical shipbuilding point of view, and would serve to illustrate that the confidence which expert opinion has in the seaworthy nature of these light craft is not misplaced.

H.M.S. *Hunter* is a typical modern destroyer, of which several flotillas have been built for the Royal Navy during the past ten years. The accident occurred on May 13, 1937, while the ship was engaged on patrol duties in the Mediterranean off Almeria, Spain, as a unit of the British force carrying out this country's part of the international patrol of the Spanish coasts.

The H class flotilla, consisting of H.M.S. *Hardy*, flotilla leader, and eight destroyers, of which H.M.S. *Hunter* is one, was ordered under the 1934 program. The ship under consideration was built by Swan Hunter & Wigham Richardson, with machinery by the Wallsend Slipway & Engineering Co., and was laid down in March, 1935, and completed in September, 1936. The principal particulars of the ship are as follows:

Length B.P., feet	312
Length, overall, feet	323
Beam extreme, feet	33
Draught, mean at standard displacement, feet and inches	8—5
Standard displacement, tons	1340
S.H.P.	34,000
Speed, knots	35½

Armament 4—4.7-inch Q.F. guns.
6 smaller guns.
2 sets of quadruple torpedo tubes.

An outline profile of the ship is given in Figure 1.

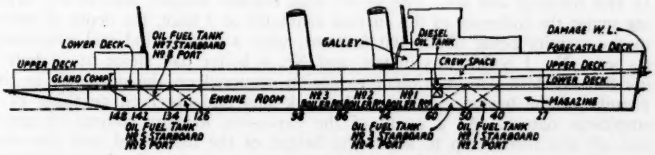


FIGURE 1.—PROFILE OF H.M.S. "HUNTER".

The hull is constructed practically throughout of D quality steel, a special steel extensively used in Admiralty warship construction, having an ultimate tensile strength of from 37 to 44 tons per square inch, and a minimum elongation of 17 per cent in 8 inches. In general, all the important structural work, with the exceptions to be stated, was riveted. Main transverse bulkheads of 6-pound plating and over, the majority of the deep frames, and the floor plates and girders under the lower deck were welded. The lower deck plating over the oil fuel tanks was riveted to the beams, but welded on the edges and butts. The shell plating, where it extended above the upper deck, was connected to the deck by welding, the gunwale angle being omitted. Where the shell plating stopped at the upper deck, the usual gunwale angle was fitted and riveted.

The welded bulkheads were generally constructed of joggled plating, with laps equal to three times the thickness of the plating, with a continuous full weld on the boundary bar side and a continuous light weld on the opposite side. The stiffeners were of flat bar or angle bar, welded to the bulkhead with a continuous light weld on both sides. Conical neck rivets were used for all plating of 12 pounds and over, straight neck rivets being used only where the plating was under 12 pounds. Where conical neck rivets were used, the holes to receive them were accurately coned beforehand, care being exercised to avoid the coning penetrating the full thickness of the plate. For D plating under 12 pounds the sharp edges of the holes were taken off by slight chamfering. All holes in the D quality steel and elsewhere where structural strength, oiltightness or watertightness was involved, were drilled, the diameter of the clearance hole exceeding the nominal diameter of the rivet by not more than 1/32 inch. The electrodes were the usual proprietary brands suitable for use with the particular materials to be welded, and the welding was all done by hand.

The rivets used in the D steel plating were of Admiralty DR quality. This is somewhat similar in composition to D steel, except that the test pieces from the rivet bars have an ultimate tensile strength of from 35 to 40 tons per square inch, and an elongation of 20 per cent in 8 diameters. Owing

to the quenching effect of the surrounding plating, the driven rivets have a tensile strength approaching the upper limit for D steel.

The rivet heads were of the shallow type, the depth of head being one-half the diameter of the rivet, compared with 0.7 diameter of rivet adopted by the principal classification societies. As will be seen from the description of the damage, these rivets performed quite satisfactorily in the region of the explosion.

At the time of this series of events the ship, except for the amount of oil fuel on board, was practically in the deep condition, that is, the standard condition, with the addition of oil fuel and reserve feed water. The oil fuel was disposed as follows: Nos. 1 and 2 tanks full; Nos. 3 and 4 just under half full; Nos. 5 and 6 empty; Nos. 7 and 8 full. The draught was about 10 feet forward and aft. The vessel with engines stopped was slowly drifting under the influence of the current estimated at 1 knot, the depth of water in the vicinity being about 100 fathoms, with a slight wind and practically no sea. No. 1 boiler was in use, and No. 3 boiler had steam at ¼ hour's notice. At 2:15 p.m., a violent explosion occurred on the port side in the vicinity of the bridge. None of the look-outs had observed anything of a suspicious nature. As a result of the explosion, a large column of water and oil was thrown up to about the height of the mast-head, and the ship immediately took a list of about 25 degrees to starboard, slowly righting herself as the compartments flooded. Examination revealed flooding to the following extent:

Magazine 27-40	Leaking and subsequently flooded to lower deck.
Oil fuel tanks Nos. 1 to 4 No. 1 boiler room No. 2 boiler room	flooded up to waterline.

No. 3 boiler room and the engine room were intact. No. 1 boiler had been forced off its seating and blown forward and over to the starboard side, but no boiler explosion occurred. No. 2 boiler had moved bodily aft about 6 inches. The ship settled down to a draught of about 18 feet 6 inches forward, and 11 feet at the cut up aft, from which it was estimated that about 900 tons of water had entered the ship, an amount equal to about two-thirds of her standard displacement. The waterline at which the ship was floating before and after the explosion are shown in Figure 1.

The ship was towed into Almeria by local craft, and after further examination, it was decided to tow her to Gibraltar, and on May 14th she left in tow by H.M.S. *Arethusa*, the passage of 150 miles to Gibraltar being accomplished in favorable weather in 2½ days. Owing to the damaged fore end, the ship was towed stern first, a low speed being necessitated by the pounding of the sea on the flat stern. Figure 2 gives a general view of the ship on arrival at Gibraltar. (Note the line of lower deck scuttles disappearing into the water.)

After docking at Gibraltar on May 16, the full extent of the damage was revealed. The explosion appeared to have taken place near the forward end of the bilge keel on the port side, and followed a path upwards and aft, to come out through the upper deck near the starboard side of the galley. The ship was cut in two at about bulkhead 60 right through the keel, and up to the lower edge of the sheerstrake port and starboard. On the starboard side, the damage showed as a more or less vertical cut, but the port side was blown in and up, so that in elevation the hole was roughly a trapezium 18 feet in length at the top and 35 feet at the keel. The damage was between

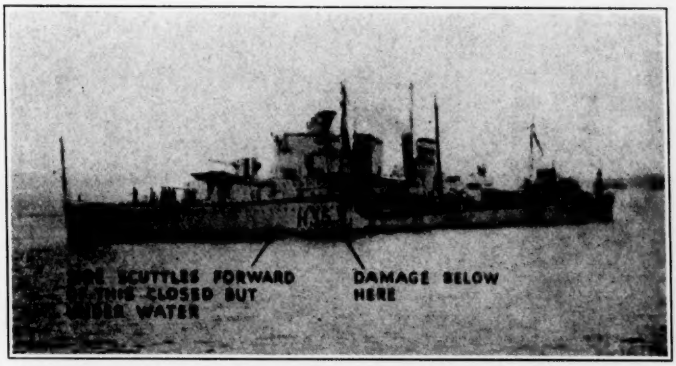


FIGURE 2.—H.M.S. "HUNTER" SHOWING TRIM BY BOW.

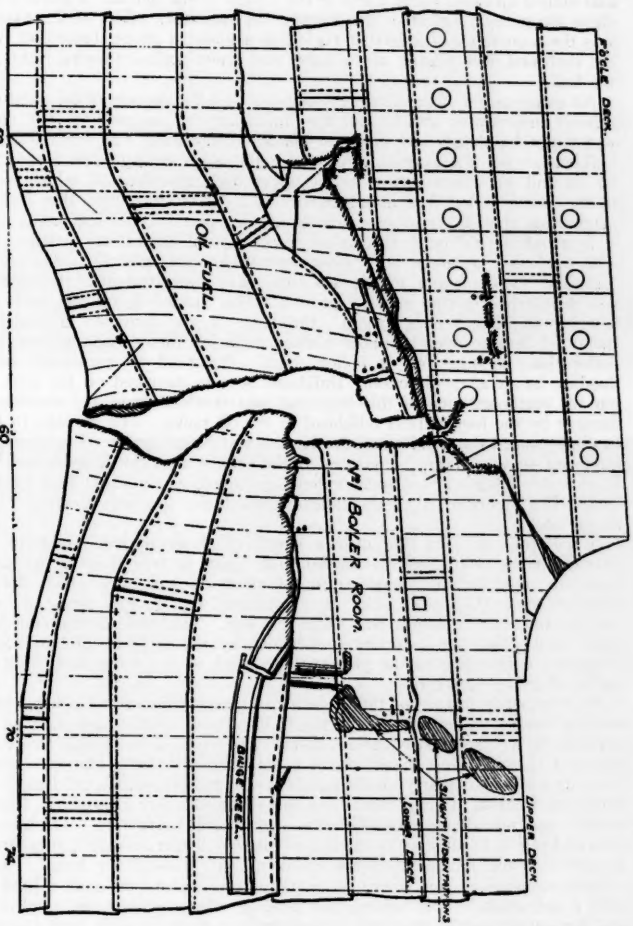


FIGURE 3.—DAMAGE TO OUTER BOTTOM PLATING, PORT SIDE.

stations 48 and 73, and all the internal structure up to the upper deck was destroyed, the upper deck being badly bulged upwards at the break of the forecastle. The flat keel between 50 and 70 was away from the dock blocks and bulged upwards about 2 feet in the middle of the length. Figures 3 and 4 show the general extent of the damage. A secondary effect of the explosion was the occurrence of a further region of damage at about station 137, where the shell and deck plating of the upper and lower decks crumpled right round the hull.

An examination of the damage illustrates the effectiveness of the subdivision against underwater attack, and the importance of maintaining the various watertight bulkheads and decks in efficient condition. The main transverse bulkheads over the portion affected by the main damage are Nos. 27, 40, 60, 74 and 86, which extend to the upper deck, and No. 50, which extends to the lower deck. The arrangements in a destroyer require that the main subdivision shall be transverse, except at such places as oil fuel tanks, where a longitudinal bulkhead is worked to divide the tanks into smaller units. The explosion occurred at a most vulnerable spot, directly under a main bulkhead, thus opening to the sea two main compartments. Bulkhead 60 was demolished in way of the explosion. This opened up oil fuel tanks Nos. 3 and 4 and No. 1 boiler room. Bulkhead 74 was distorted generally and sustained damage over its upper portion by being forced back against No. 2 boiler thus flooding No. 2 boiler room. Bulkhead 86 prevented further flooding in an after direction. Bulkhead 50 was damaged on the port side, but the starboard side of this bulkhead was shielded from any considerable damage by the longitudinal bulkhead in the oil tanks. The damage to bulkhead 50 caused the flooding of the Nos. 1 and 2 fuel tanks. The damage to bulkhead 40 was slight. The toes of the brackets on the longitudinals perforated the bulkhead to a small extent, and there was a slight leak near the keel. The damage to this bulkhead caused the gradual flooding of the magazine.

It will thus be seen that over a length of about 80 feet—equal to one-quarter of the ship's length—the hull was open to free flooding up to the waterline, with an additional length of about 24 feet over which flooding occurred up to the lower deck. It is estimated that in this damaged condition the metacentric height was about 1½ feet. The value of carrying bulkheads well above the waterline is indicated by the presence of bulkhead 40 (Figure 1), resulting in the preservation intact of the waterplane from this bulkhead to the fore end.

An interesting feature of this accident is that it illustrates the behavior of welding under explosive force. Much has been written and said of the strength of welding under various tests, but here is a large structure under the most searching test of all, and it is satisfactory to note that the welding stood up well, particularly on the bulkheads, which are of thin mild steel, and where the welding in many places had to withstand severe crumpling. Figures 6 and 7 are indicative of the efficiency of the welded structure. The welding showed itself to be sufficiently flexible to take up distortion which, in a riveted structure, would have caused the rivets to pull through or break. Some failures occurred at laps where the plates were joggled. At such a joint the weld is subjected to both tension and bending when the structure is stressed, and the author would welcome a more extensive adoption of butt joints in welded structure, thus eliminating joggling. In this and other directions it would be well not to carry into welding technique the forms and methods to which we have become accustomed in general riveting practice.

In examining the behavior of the riveted structure it will be realized that when relatively thin plates are riveted together, failure tends to take

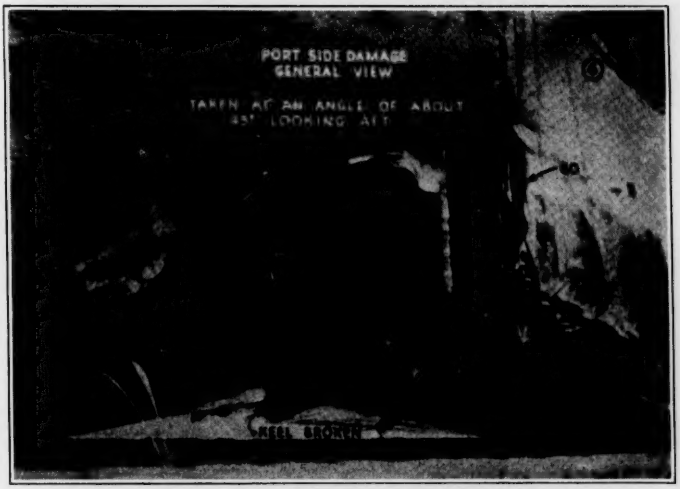


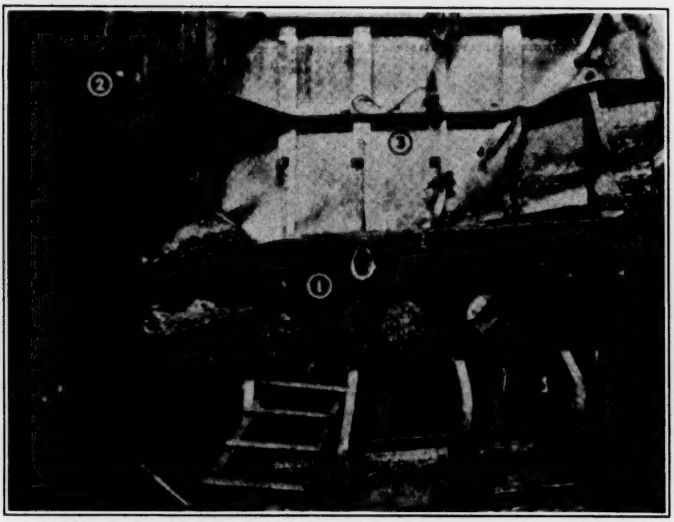
FIGURE 4.—TAKEN AT AN ANGLE OF ABOUT 45 DEGREES LOOKING AFT.

(1) Middle line divisional bulkhead cut away as badly damaged. Note bulkhead has torn away from brackets.

(2) Bulkhead torn in way of bracket due to lateral explosive force on bracket.

(3) Bulkhead cut away where too badly damaged to be of use in temporary repair.
Welding has stood well in spite of crumpling. Starboard side of bulkhead intact.

FIGURE 6.—BULKHEAD 50, PORT SIDE, LOOKING FORWARD, BETWEEN FORWARD OIL FUEL TANKS.



(1) Port boiler bearer.
(2) Bulkhead 74 between Nos. 1 and 2 boiler rooms.
(3) Port side plating.
Note how welding has stood up on brackets to bearer. No. 1 boiler having been removed enables this structure to be seen for first time.

FIGURE 7.—AFTER END OF NO. 1 BOILER ROOM SHOWING PORT BOILER BEARER.

(1) Port boiler bearer.
(2) Outer bottom plating turned up by explosion.
(3) Port side outer bottom plating.

FIGURE 8.—FORWARD END OF NO. 1 BOILER ROOM SHOWING FORWARD END OF BOILER BEARER (P). (A CONTINUATION OF FIGURE 7.)

place in the plates rather than by shear of the rivets. A marked feature of the damage was the excellent way in which the rivets withstood the shock, and such rivets as were not holding had generally pulled through at the points. As previously remarked, the shallow-headed rivets stood up remarkably well.

The D quality plating has shown good resilience and ductility. Typical examples of the behavior of this plating are shown in Figures 6 and 8. It would appear that during the explosion the boiler bearer caused the crumpling of this bracket and the deformation of the bulkhead stiffener. If this is so, and no other explanation suggests itself, then the boiler bearer must have been momentarily deflected to the extent of about 5 degrees, subsequently returning to the position shown in the illustration. Such movement of the structure is indicative of the excellent ductility of the material, and the crumpling of the plate in bulkhead 74 clearly indicates that large local shear forces were present.

The secondary damage at about station 137, previously referred to, presents some curious features, and so far as the author can ascertain, no previous case of such damage is recorded. The whole of the skin plating and the upper and lower decks have crumpled, the ship presenting the appearance of having been pushed together from both ends. The damage is extremely local in the fore-and-aft direction, and is confined to the forward end of Nos. 7 and 8 oil fuel tanks, which were full, these tanks being immediately abaft Nos. 5 and 6 tanks, which were empty. There were no signs of similar failure of the structure at any other point. It was reported by officers who were aft at the time of the explosion, that a distinct whip was felt in the structure.

Various possible causes of this damage have been considered, but no really satisfactory explanation can be given as to why the structure failed here and not elsewhere. The impulsive force of the explosion under the fore part of the ship would produce a bending moment on the structure of the form indicated in Figure 9, the maximum at X occurring in the region of the

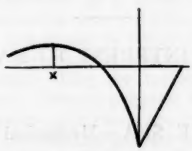


FIGURE 9.

damage. Such a bending moment, while it might account for the crippling of the upper deck, does not account for the crippling of the keel, which would require a bending moment in the opposite direction. It appears more likely that the failure was due to a direct compressive stress set up by the directional force of the explosion. The path of the explosion, as traced by the damaged structure, is from a point on the port side near the forward end of the bilge keel, to a point on the starboard side of the upper deck, abreast of the galley. The explosive force appears, therefore, to have had a fore-and-aft and an athwartship component. It may be that this fore-and-aft component caused the failure, the position of the failure being determined by the combination of loading and stiffness of the structure. As in a chain, the structure would fail at its weakest link, without signs of failure elsewhere. Some support is given to this explanation by the fact that measure-

ments of the ship in dock do indicate a bending to starboard in the vertical plane, apparently caused by the athwartship component of the explosive force.

It may be observed as a point of interest, that the present practice of using fireproofed wood wherever possible received ample justification. Though quantities of oil fuel were thrown about by the explosion, and small fires occurred, in no instance was difficulty experienced in quenching them. Fireproofed wood was found with the paint badly scorched, and but for the fireproofing serious fires might have occurred.

Apart from the complete wrecking of No. 1 boiler room, with its boiler and auxiliaries, there was practically no other machinery damage. The boiler was torn from its seating and thrown bodily over to the starboard side, and, though severely damaged, no explosion occurred. The low power room, wireless office and Diesel dynamo room were also wrecked.

To conclude the description of the damage, the First Lord of the Admiralty stated in the House of Commons on June 7 that an examination of the report of the Court of Enquiry confirmed the statement previously made that the damage was caused by a mine, and, having regard to the nature of the damage and other circumstances, there was a high degree of probability that the mine was moored.

It was decided that temporary repairs should be effected at Gibraltar to enable the ship to proceed to Malta for permanent repairs. The temporary repairs necessitated cutting away the damaged portions of the hull and clearing the wreckage from No. 1 boiler room. A temporary structure was then built to join the bow portion to the remainder of the hull. These repairs were carried out in 12 weeks, and the ship left Gibraltar under her own power, steaming on one boiler, on August 18, arriving at Malta on August 21, the speed on passage being about 13 knots.

In conclusion, the author desires to express his thanks to Mr. S. V. Goodall, C.B., O.B.E., Director of Naval Construction, for permission to publish this paper, and to Mr. H. E. Skinner, B.Sc., R.C.N.C., for his assistance in its preparation.

MISCELLANEA OF INTEREST TO NAVAL ENGINEERS.

A NEW ERA ON THE SEA.—Mechanical Engineering, New York, N. Y., January, 1938.

It was on May 26, 1819, that the *Savannah* left the city of that name for Liverpool, the first ship equipped with steam boilers and engines to cross the Atlantic Ocean. To be sure, on her 29 days' voyage she raised steam only six times and ran her engines only 80 hours, but her trip began a century of steamship supremacy on the Atlantic. On December 17, 1903, at Kitty Hawk, the Wright brothers made their first demonstration flight with a heavier-than-air craft under power. On October 15, 1937, the United States Maritime Commission released a report in which this country was advised to turn its eyes away from superliners of the *Normandie* and *Queen Mary* type, and study the super flying boat as a means of rapid transatlantic travel in the luxury class. On December 11, 1937, Pan American Airways Corporation asked eight manufacturers to submit preliminary engineering sketches of 100-passenger flying boats capable of crossing from New York

to Europe, nonstop, in 17 hours. These events, and others that complete the cycle, are evidence of the steady advance of technology, with implications too numerous and far-reaching to be easily summarized.

Fortunately, the section of the Maritime Commission's report dealing with the superliner is abstracted in this issue, as is also an article by George J. Mead, of the United Aircraft Corp., in which mention is made of the need for engines of 2000 to 3000 H.P., for without engines of high power the large, fast, flying boat will be hard to produce.

The general requirements which the manufacturers are asked to consider include a pay load of 25,000 pounds, a cruising range of 5000 miles, a cruising speed at sea level of 200 M.P.H., stateroom, dining-room, and lounge facilities for 100 passengers, and accommodations for a crew of 16. After the preliminary engineering sketches have been considered, it is announced, manufacturers who have submitted feasible plans will be asked to prepare detailed designs and engineering specifications for new boats. It is hoped that the proposed boats will be in transatlantic service in 1941.

Thus, a daring and challenging objective has been set for the aircraft and engine manufacturers of this country—one which they have the courage to attempt; and no one who has followed progress in the field of aeronautics doubts that there exist the skill and ability of the manufacturers to achieve the ends sought. For a country whose frontiers have, according to popular belief, disappeared, the task ahead holds great encouragement. One wishes that economic and social problems could be so easily stated and could hold the promise of such immediate and satisfactory solutions.

INDUSTRIAL USES FOR SILVER.—Technical News Bulletin of the National Bureau of Standards, Washington, D. C., January, 1938.

In Technical News Bulletin 244 (August, 1937) there appeared an outline of the research program sponsored by a group of leading American silver producers to develop new industrial uses for silver.

Since appointment of the last of the 15 research fellowships at the various laboratories engaged in this investigation about the first of June, 1937, there has been an active study made along the various lines mapped out in the earlier report on this project. Definite progress has been made in each field studied, and, in several instances, indications are that the particular researches will, when completed, be of considerable interest to industry.

At one institution a Silver Research Project Fellow has been investigating the antifriction properties of silver and silver-rich alloys. Amsler wear tests evaluate the load which produces a given coefficient of friction and give information regarding the tendency of the alloy to gall and score a steel journal. The effect on the antifriction qualities of a great many elements added to pure silver has been determined. Pure silver has been found exceptionally qualified for use as a bearing material, most alloy additions producing inferior results. The data being obtained are of special interest because steel-backed bearings lined with nearly pure silver have come into commercial use within the year, being standard equipment on certain aviation engines. Because of the resistance silver offers against galling and scoring, it is being considered for shims and metallic packing. The latter application takes advantage, also, of the resistance of silver to heat and corrosion.

Two research investigators studying the electrodeposition of silver and of silver alloys have developed methods for obtaining adherent deposits on steel

and for codeposition of a number of elements with silver. The development of further improvements in electroplating technique is expected to extend materially the usefulness of silver plating in the chemical and other industries.

The study of silver slip rings and silver-graphite brushes for rotating electrical contacts has demonstrated marked advantages for these materials over carbon or copper-graphite brushes, and copper slip rings or commutators. Contact voltage drop is very much less, operation follows the Ohm's law relationship closely, and much higher current densities can be tolerated. Furthermore, there is much less polarity effect when using the silver contacting surface. Manufacturers of electrical equipment have already taken cognizance of these test results, which may lead to improved design in certain electrical equipment.

Very satisfactory results have been obtained with silver as a catalyst in the oxidation of ethyl alcohol, operating at conditions varying considerably from commercial practice.

Data are being obtained on heat transfer through silver. The use of a commercial 50-gallon vessel of pure silver has reduced a batch operation cycle from 48 hours when carried out in glass-lined equipment to only 4 hours, with an increase in thermal economy and with less degradation of the product. Scientific data on such performances are, however, lacking, and it is believed that this research will contribute heat-transfer data of use to the mechanical and chemical engineer.

The ability of silver salts to act as potent fungicides has been demonstrated by a Silver Research Project Fellow and the agricultural possibilities are being studied in some detail. This research also appears very promising in connection with water sterilization, particularly for fish hatcheries.

A thorough study of the medical literature on argyria, or alleged silver poisoning, has been made as a preliminary step by the Research Fellow investigating the toxicological properties of silver. Very little reliable information on this subject is available, and further study is needed to evaluate the extent to which this may be a problem of practical interest to other than the medical profession. Another research worker in the medical field is studying the "mechanism" of the action of silver on bacteria by determining what particular chemical group of the organism reacts with silver or the silver ion.

The permeability of hot silver to oxygen has been considered as a means of fractionating air. Calculations show interesting possibilities, and experimental work is being undertaken to verify the calculations and the practicability of using this principle in enriching blast-furnace air, for example. The solubility of oxygen in molten silver offers another possible line of attack, and this also is being considered.

The effect of additions of silver in small amounts (up to about 5 per cent) to the engineering alloys is being studied on a comprehensive scale through cooperation of five men working at three different institutions. These same research workers are also noting the effect of small additions of other metals to pure silver. In general, the response to various annealing and hardening treatments and to corrosion is being studied. It is expected that data will also be obtained on castability, mechanical properties, electrical conductivity, and other properties likely to be of special interest. Almost 200 alloys have been prepared for this work.

Special attention is being devoted to the lead-silver solders containing from about 2 to 6 per cent of silver, with and without other additions, as competitors with the lead-tin solders and as intermediate temperature solders.

Long-time creep-test data are being obtained on soldered joints made with such alloys, at both room and elevated temperatures.

Another investigation sponsored by this project has to do with the effect of silver additions to storage-battery grids.

Technical data are being gathered on all silver-alloy systems, the patent literature dealing with silver; and the use of silver in the chemical industry.

A. J. Dornblatt, senior research associate at the National Bureau of Standards, representing the American Silver Producers, has recently visited some 60 companies and research laboratories to acquaint them with the objectives of the various researches, and the results being obtained on this project, and to solicit suggestions and data from their staffs. Parties interested in any phase of the American Silver Producers' cooperative research are invited to correspond with the Bureau for details.

PYROTENAX ELECTRIC CABLES. — Shipbuilding and Shipping Record, London, England, October 28, 1937.

Reference was made in our issue of October 14 to the opening at Hebburn-on-Tyne of a factory for the manufacture of a new type of cable by Pyrotenax, Limited. Pyrotenax cables are magnesia-insulated copper-sheathed electric cables, and provide the shipping community with a method of wiring which is not only new but also has certain advantages over conventional types. They are really fireproof, very robust, and secure both these features without being obtrusive or costly to install.

The use of magnesia as insulation instead of rubber or paper has been developed by a company in France, and Pyrotenax, Limited, is now manufacturing at Hebburn. Shipyards at St. Nazaire, Dunkerque and Marseilles have already used the new cable and many industrial installations have been undertaken in Great Britain. The cable is not only suitable for ship wiring, but also has qualities of value for use in offices and shore establishments.

CHARACTERISTICS.

The copper sheath of the new cable secures watertightness and resistance to corrosion, but in itself would present no very great difference from existing practice. It is the insulation material and its compressed state that are responsible for the special characteristics. The mineral magnesia is hygroscopic and has no important mechanical qualities, but in the course of the manufacture of this cable it is so compacted that it may be said to reinforce the copper sheath from the inside, so that it is difficult to deform the cable by casual blows. Repeated hammering of the cable results in flattening, but the process has to be taken to great lengths before the magnesia insulation is interrupted and failure results. Moreover, the magnesia is noninflammable and does not support combustion, so that there is nothing in the cable to feed a fire. Indeed, demonstrations have shown that the cable can be raised to temperatures approaching the melting point of copper without any change in electrical characteristics or deformation. This compares more than favorably with either vulcanized indiarubber or paper insulation, and secures an advantage for the new cable in respect of insurance risk.

The excellent mechanical support afforded by the compressed magnesia to the conductors also enables the cable to be bent through sharp angles without any decentralization resulting. This is a useful feature in surface work, not only in a ship, but also in office installations. Again, the cable is

relatively stiff and behaves practically as a metal bar, so that it needs supports only at relatively wide spacing. For ship work, it is suggested that two or more Pyrotenax cables in parallel are preferable to the usual comparatively large diameter lead-covered cable, and these can even be secured by screws in blind holes in a bulkhead, whereas the bigger diameter cable requires bolts piercing the bulkhead.

Another characteristic of compressed magnesia is its high thermal conductivity. If necessary, the conductors in Pyrotenax cables can be run at current densities much higher than those allowable in more conventional types. The sheath in such a case acts as effective radiating surface; indeed, the voltage drop is the factor which becomes the real limitation. This feature is also of interest where cables are bunched in conduits, because the higher temperature of the cables remote from the surface is of no consequence if they are of Pyrotenax construction, and it also avoids any ill-effects if in emergency conditions the cable is called upon to carry very heavy overloads.

During manufacture, the magnesia is first formed into blocks or bobbins complete with holes for the conductors. These bobbins, after having been dehydrated by having their temperature raised sufficiently in a rotating-hearth electric furnace, are introduced into a copper tube, which has been previously straightened and cleaned internally, in such a way that the conductor holes register. Precautions are taken to prevent the magnesia taking up moisture from the air during this process, and when the tube has been filled, one end is swaged to secure a grip for a drawing machine. After the cable has been drawn down a predetermined amount, it is annealed and the drawing process repeated. According to the size of cable in question, several such processes may ensue and the cable is finally annealed, tested and prepared for delivery in the form of coils wrapped in hessian; it is not usually wound on drums. Joints of cable lengths can be made at the factory or on site and special fittings are provided for connections to section and distribution boxes, switches, etc. Simple tools are available for stripping off the sheath where connections have to be made and erection is claimed to be an easy matter. Various sizes of single and multi-core cable are available for voltages up to 600.

LUBRICATING OIL FOR CIRCULATING SYSTEMS OF STEAM TURBINES.—Combustion, New York, N. Y., December, 1937.

Reliability of operation and continuity of service are two very important factors in steam turbine practice. Turbines are often expected in industrial plants to run continually for a week or more and for a year in central power stations. If the oil in the system fails, the turbine must be taken out of service and unscheduled shutdowns are costly. Because lubrication has a definite effect upon reliability, this subject is always of interest to turbine operators.

The majority of turbines are lubricated by a pump-pressure-circulation oiling system, although the smaller units are sometimes designed with ring-oiled bearings. In the circulating type of unit the oil performs three different duties. It cools as well as lubricates the main bearings and the governor parts, and makes use of its pressure to actuate the governor mechanism. In geared units, the same oiling system lubricates and cools the gears.

The problem of lubricating the main bearings of a turbine is not difficult in so far as the bearings alone are concerned. Unit pressures are not heavy, and speeds during actual operation are high enough to produce perfect oil-

wedge action. In fact, the bearing situation is usually so favorable that films of oil completely separate the journals and bearings at all times, except during periods of starting and stopping and idleness. Temperatures, induced through the shaft from the steam end, are kept within reasonable limits by flooding an excess of oil over the bearings and journals, the heat being subsequently removed from the oil by means of coolers. Much the same condition exists in the governor mechanism, so that the problem is not difficult from a strictly lubricating standpoint, nor are any serious difficulties presented in using the oil as an hydraulic medium for governor action.

The principal problem in turbine lubrication is to circulate the oil for long periods of time without producing dangerous changes in its character. The most objectionable changes are the formation of deposits, sludges or emulsions. Oil refiners, turbine builders, equipment manufacturers and operators are all bending every effort to minimize these objectionable formations in turbine oils. The petroleum industry has already produced lubricating oils which under favorable operating conditions function satisfactorily in turbines without replacement for periods of 10 years or more. Nevertheless, intensive research is still under way to develop improved products.

VISCOSITY REQUIREMENTS.

In considering the requirements of a turbine oil, the viscosity is a characteristic which must be given careful attention. As viscosity decreases, the ability to maintain a fluid lubricating film also decreases. Therefore, light-bodied oils are not best suited for heavy unit bearing pressures. On the other hand, heavy oils produce a noticeable drag on moving surfaces, necessitating increased power input which is dissipated as increased heat in the bearings. Increased heat causes more rapid oil deterioration. Heavy-bodied oils are, therefore, less suitable for the high speeds. Moreover, the action of gravity, in causing impurities to settle out of oil, is slower for heavy than for light oils.

In deciding upon oil viscosity, it is important to select the lightest body that will maintain a separating fluid film between moving surfaces. Experience has shown that for direct-connected units an oil having a viscosity of 150 sec Saybolt Universal at 100 F. is a good choice. At the present time, European practice tends to favor somewhat heavier oils. In geared turbines, the unit pressures on the gear teeth (due to line contact) are considerably higher than the unit bearing pressures, and therefore the oil must be selected to sustain these higher tooth pressures. A Saybolt Universal viscosity of 320 sec at 100 F. is considered correct for stationary geared units.

During operation, the turbine shaft is spinning at a speed sufficient to drag the oil films completely across the weight-carrying areas of the bearings. This action lifts the shaft and floats it on a film of oil so that there is no longer any contact between shaft and bearing. With this condition existing, the problem of lubricating turbine bearings becomes a matter of pure hydraulics, and the oiliness characteristics of the oil are of little importance. If this were the only condition to be met, any liquid of suitable viscosity could be made to serve the purpose, but the turbine must be started and stopped, and during these periods the shaft speed is insufficient to form or maintain the film of oil. Under a microscope, even the smoothest of bearing surfaces appears as a rough series of hills and dales. When two such surfaces rub across each other with no separating oil film, the hills strike and are levelled off, resulting in heat and wear. At full speed the turbine bearing creates a separating film far thicker than the height of the hills, but at low speed the hills clash, and a cushioning medium is needed to absorb the shock and

minimize the damage. Metal-to-metal contact does occur during starting and stopping periods and oil is required to prevent damage to the rubbing surfaces.

OIL A COMPLEX CHEMICAL SUBSTANCE.

Petroleum has no specific chemical formula. It is one of the most complex chemical substances known, and consists of a countless number of varieties of molecules, all, however, being composed of hydrogen and carbon. Impurities such as sulphur, oxygen, nitrogen, etc., are also usually present in crude petroleum. The different types of molecules have different characteristics ranging from the unstable unsaturated molecule, which is striving always to complete itself by chemically uniting with something else, to the completely stable molecule which resists change.

In refining turbine oil, the aim is always to remove the groups of molecules that are unstable and to preserve those which are stable, keeping in mind, however, that this process of removal cannot be carried too far without sacrificing lubricity. To cushion the interlocking hills of the slowly moving bearing surfaces, an oil is needed which will cling to the projecting points under tremendous local pressures. A bond, approaching actual chemical union between the metal and the oil, is needed, but such a bond cannot be secured with the completely saturated type of petroleum molecule even though it is quite possible (by intensive refining) to produce oil consisting only of the entirely stable hydrocarbons. Such oils are known as U.S.P. White Oils and Technical White Oils. In order to secure the best bearing protection under conditions approaching metal-to-metal contact, it is desirable to have present some of the molecules which possess a greater ability to bond with the metal as stated above. This is best accomplished by preserving the natural lubricants of the original oil.

RESISTANCE TO CHANGE MOST IMPORTANT.

After the correct viscosity of the oil is established, and adequate lubricity is provided for conditions approaching metal-to-metal contact, the turbine-oil problem then becomes a question of durability, resistance to change and chemical stability.

In the turbine the oil is repeatedly subjected to pressure, to heat, to spraying from bearings, to mixing with air, and to contamination with water. The better the oil quality, the greater the resistance to these circumstances, but where unstable hydrocarbons are present, they will eventually absorb oxygen from the air. Heat always accelerates any chemical process, and in the turbine, the higher the oil temperature, the faster this oxygen absorption will proceed. Ordinarily, a temperature of 130 F. is considered good practice for oil returning from the bearings, although units are in satisfactory operation at 170 F. The higher temperatures, however, definitely complicate the problem of stability. Upon absorbing oxygen, petroleum hydrocarbons become acidic. The organic acid so formed increases the oiliness of the oil, due to an increased absorption on the metal surface of the bearings.

This increased bonding ability is thought to be due to the orientation on the metal of strata of polar molecules. Polar molecules are those which contain atoms or groups of atoms, the valence of which is not completely satisfied, thus providing residual valence which attaches to the metal. Metal soaps may also be formed by reaction of organic acids with the metals used in construction of the turbines. If water is not present, this action is not usually troublesome, although in aggravated cases, the oxidized hydrocarbon can be of such type and such strength as to corrode copper

parts of the system. Where water is present, the soap acts as an emulsifier to create emulsions that are hard to remove.

Pure water and pure oil can be violently mixed and, upon ceasing the agitation, the oil and water will separate quickly and completely. The introduction of a certain type of additional impurity will, however, cause the oil and water mixture to remain more or less permanently emulsified. Minute particles of solid matter that will readily absorb either oil or water will act as emulsifiers. Substances that reduce the surface tension of either oil or water will cause persistent emulsions. These emulsions may be of a thin fluid nature or may be of a thick sticky plastic character, but in all cases they are potential causes of oil-pipe plugging. The preventive measures taken against emulsions are (*a*) to use oil with high resistance to oxidation, (*b*) to keep oil temperatures moderate, (*c*) to use oils that separate rapidly from water and (*d*) to keep water out of the oil.

OXIDATION CAUSES ACIDITY.

The organic acids created by the oxidation of the less stable hydrocarbons are of numerous types according to the particular combination of carbon, hydrogen and oxygen that takes place. Some types are more active than others, but all are soluble in oil when first formed.

As the percentage of acidity increases, a point of saturation is finally reached where any additional oxidation causes the precipitation of the oxidized hydrocarbon as a microscopic solid particle. The saturation point of hot oil is higher than that of cold oil, or in other words, cold oil will not hold as much oxidized petroleum sludge in solution as hot oil will. Therefore, in a turbine system the excess oxidized portions are precipitated from the oil at the coolest point of the system.

The first step in the creation of either emulsion or sludge is the formation of the oxyhydrocarbons. The measure of the extent of this reaction, in so far as the formation of acidic materials is concerned, is determined by the amount of alkali that is required to neutralize the acidity. The neutralization number of an oil is expressed in terms of the number of milligrams of potassium hydroxide necessary to neutralize the acid in one gram of oil. The neutralization number alone does not identify the type of acid nor the percentage present. Different organic acids have different neutralization numbers. Therefore, the neutralization number is an uncertain index of the sludging probabilities of an oil. Because of this it has been found necessary to interpret neutralization numbers in the light of actual experience in service with the particular oil under consideration and the particular circumstances of operation. Certain chemical structures of oil molecules may have a high neutralization number and still not sludge, the acids remaining in solution without causing trouble.

DESIRABLE DEGREE OF REFINING.

In general, the intensively refined oils will have higher neutralization values in use without precipitating sludge, whereas the mildly refined stocks do not show as high acidity and may form sludge more readily. Refiners of high-grade turbine oils select crudes and methods of refining which will assure the greatest resistance to sludge that is consistent with low acidity. A neutralization number of less than 0.75 holds little probability of sludge. For values of over 0.75 it is necessary to consider the type of oxy-acids before predicting sludge probabilities. The Steam Emulsion Test as applied to used oils is of assistance in determining whether the oxyhydrocarbons

present are of a type that will cause sludging associated with emulsion formation. Sludge fouls the oiling system, interferes with proper cooling, restricts oil flow and eventually causes shutdown for cleaning.

The oil industry has concentrated on the elimination of the hydrocarbons that are susceptible to oxidation. Present refining methods make it possible to carry this elimination to such extremes that valuable as well as undesirable materials are eliminated. For instance, the elements that furnish oiliness during periods approaching metal-to-metal contact must not be removed. There are present in the natural oil, types of compounds that act to retard the union of oil and oxygen, thus prohibiting the formation of the petroleum acids. Too drastic a treatment of the oil during refining removes these highly desirable natural inhibitors.

TYPE OF TURBINE OIL THAT IS MOST GENERALLY EMPLOYED.

At the present time the type of turbine oil in use in the greatest percentage of the world's important turbines is an oil that has been refined to remove the maximum percentage of unstable hydrocarbons without dangerously decreasing the portion of less stable elements that act as natural metal bonds and as natural inhibitors. The refiners are looking continually for improvements. Development work is under way along lines of supplying artificial lubricity and artificial inhibitors. Materials have been developed that retard the formation of oxyhydrocarbons for a certain period of time and appear to hold possibilities for future improvement. Experience, however, has been limited to turbine runs which are short as compared to the many instances of 10 to 15 years of service with conventional oils.

The factors of viscosity, lubricity and stability are vital items in a turbine lubricating oil. The stability item is particularly important and is very closely allied to oil quality. Most of the oil difficulties experienced by operators are influenced by oil stability, and turbine oil manufacturers have attempted to produce lubricants that resist change while in use. Thirty-five years of study of oil in action have produced the present-day quality lubricant. The higher quality oils of today are capable of giving service extending over a period of many years. Even better oils are hoped for, but definite proof of progress must await the time when these newly developed products have established definite superiority in long periods of service.

HEAVY TUNGSTEN ALLOY.—Engineering, London, England, December, 3, 1937.

As mentioned on page 5 of our 142nd volume (1936), a new heavy alloy has been developed in the Wembley Research Laboratories of Messrs. The General Electric Company, Limited, Magnet House, Kingsway, London, W.C., mainly for making containers for the large quantities of radium now used in therapeutic work, although applications have since been found for it in engineering work. If radium is to be employed efficiently in its therapeutic applications, the actual container must be as small as possible, and since the absorption of the harmful γ-radiation by metals is directly proportional to their density it will be obvious that a smaller container can be made with metal of high density than with one of lower density. Such containers, or bombs, as they are called, have usually been made of lead, the density of which is 11.35 grams per cubic centimeter, and may weigh from 50 pounds to 100 pounds. The nosepiece of the bomb has sometimes been made of gold, but this metal is, of course, too costly to be used for the bomb itself.

The only other metal which is reasonably cheap and has a density comparable with that of gold is tungsten, but the high density of this metal is only attained by sintering tungsten powder at about 3000 degrees C., and there are no available means for heating large masses of the metal, of the order of 1 hundredweight, to such a high temperature. The problem has, however, been solved by mixing tungsten powder with a small proportion of a metal of lower melting point, so that a liquid phase is formed on heating the mixture to a moderate temperature. If, by this treatment, the tungsten particles are wetted by the liquid metal, shrinkage of the mass occurs and densities closely approaching the theoretical value of 19.3 grams per cubic centimeter are obtained. Nickel and copper have been found to be suitable additions for this purpose. About 5 per cent to 10 per cent of a mixture of nickel and copper powder is added to the tungsten powder, which is then pressed to the required shape in a steel die and heated in an atmosphere of hydrogen to a temperature of 1450 degrees C. Since a linear shrinkage of about 20 per cent occurs in this sintering process allowance for this must be made in designing the dies. The alloy generally used for making radium bombs contains 4 per cent copper and 6 per cent nickel and the density of the finished pieces lies between 16.3 grams and 17.0 grams per cubic centimeter. The density of the new alloy is, therefore, more than twice that of steel and some 50 per cent greater than that of lead. We understand that practically all the large hospitals in this country have been equipped with radium bombs of this alloy. These bombs are made of various forms to suit special requirements, but they are usually about 6 inches in diameter with a wall thickness of about 1½ inches. It is of interest to note that nearly a ton of tungsten has already been used for the production of radium bombs.

The microstructure of the alloy consists, as would be expected, of comparatively large spherical grains of tungsten embedded in a matrix of copper-nickel-tungsten solid solution, the structure combining the high strength and elasticity of tungsten with the toughness and ductility of the copper-nickel alloy. The tensile strength of the alloy is 40 tons per square inch, the yield point 37 tons per square inch, the elongation 4 per cent on 1 inch, and the elastic modulus 32×10^6 pounds per square inch. Of the other physical properties the following may be mentioned: Brinell hardness, 250-290; weight per cubic inch, 0.6 pound; coefficient of expansion, 5.6×10^{-6} per degree C. (0 degree to 400 degrees C.); thermal conductivity, 0.25 C.G.S. unit; specific resistance, 1.16×10^{-5} ohm per cubic centimeter, and electrical conductivity, 0.86×10^5 mhos per cubic centimeter. From these figures it will be noted that the tensile strength, yield point and hardness are comparable with those of alloy steel, the thermal conductivity is twice that of steel, and the coefficient of expansion about half.

A point of interest is that while tungsten itself is practically unmachineable, these alloys can be readily machined with ordinary tools, although when large surfaces have to be machined it is advantageous to use a tool of the cemented tungsten-carbide type. Drilling, tapping and screwcutting present no difficulties, the threads on the bomb being perfectly formed. The alloys have the color of steel, take a high polish, and are completely resistant to atmospheric corrosion. If required, however, they can be plated with nickel, cadmium and other metals. Brazing or silver soldering can be done with the usual fluxes, but the alloys cannot be soft soldered. The most satisfactory method of joining is, however, hydrogen brazing with nickel or copper-nickel and this method has been extensively employed in the construction of radium containers. Owing to their high density these alloys have been employed for balancing the crankshafts of internal-combustion engines and have also been

used in the manufacture of gyroscopes and gyro-compasses. One of their most important uses at the present time, however, is for the arcing contacts of heavy-current circuit breakers. This latter application is in no way dependent on the high density of the alloy, its utility resulting from the great resistance of tungsten to the destructive effects of the electric arc. The method of manufacture by die pressing lends itself particularly well to the production of the shapes usually required for these contacts. The arcing tips are brazed on to copper or steel contact arms, and, owing to the high melting point and low vapor pressure of tungsten, they resist burning under conditions which would result in the rapid destruction of ordinary copper contacts.

METALS BATTLE HOT WATER AND STEAM.—Power, New York, N. Y., Mid December, 1937.

Now that commercial temperatures approach 1000 F., the oxidization of steam piping by superheated steam is a practical matter. At Purdue University Dean A. A. Potter, Prof. H. L. Solberg and Prof. G. A. Hawkins are searching out the facts. Prof. Solberg revealed their findings in a session devoted to power-field chemical problems.

The Purdue experimenters tested the oxidizing effect of high-temperature steam on steels of varied composition. Pressures ranged up to 1600 pounds, temperatures normally to 1100 F., with a few short runs at 1200 F., and plans for 1300 F. The amount of oxide produced was measured directly, after trouble with indirect determinations by hydrogen measurement.

Steam velocity and steam pressure had little effect, nor did any of the steels oxidize seriously at temperatures below 1000 F. Beyond that point, oxidation increased rapidly with temperature. Of the many steels tested, best results were obtained with 18-8 alloys, worst with low-carbon steel.

In a supplementary presentation, Dean Potter concluded that the ideal steel to resist high-temperature steam should form a thin, dense oxide scale, one not likely to crack off and expose the metal to further attack. New equipment planned for the Purdue Laboratory will permit simultaneous testing of 35 different materials, he said.

In the discussion, C. H. Fellows told of the work done by Detroit Edison, starting in 1928. Detroit is cooperating with Purdue on the present experiments, and is working independently with "cages" of steel bars inserted in high-temperature steam lines. After 3840 hours' exposure at 1100 F., 18-8 alloy was least affected, low-carbon the most, with other compositions covering the intermediate range.

For years the battle of the chemists has raged around the "intercrystalline cracking" of steel in water solutions—what was once called "caustic embrittlement." Engineers cheer on the side lines because a real understanding of this trouble will save boiler operators a lot of grief. This year's contribution came from W. C. Schroeder, A. A. Berk and R. A. O'Brien, all of the U. S. Bureau of Mines. Their work was carried out with the cooperation of the Joint Research Committee on Boiler Feedwater Studies.

Most interesting was their laboratory finding that lignin sulphonate, concentrated sulphite waste liquors, Philippine cutch and quebracho prevented cracking even when a very high stress was applied at elevated temperature. This protection was not destroyed by high concentrations of sodium silicate or sodium hydroxide. The sulphite liquor was found suitable at all temperatures up to 250 C. Definite temperature ranges had to be observed with all the other compounds tried.

It was also found that a high concentration of sodium sulphate will prevent failure of boiler steel in tension in sodium hydroxide-sodium silicate solutions if two conditions are satisfied: (1) stress in metal must be practically constant while it is in contact with the solution at elevated temperature; (2) the sodium-hydroxide concentration must not greatly exceed 25 grams per 100 grams.

W. O. Taff and Profs. H. F. Johnstone and F. G. Straub, University of Illinois, reviewed their experiments on the decomposition of sodium sulphite solutions at high temperatures. The sulphite is now widely used to prevent corrosion by removing the last traces of dissolved oxygen. Four-hour tests, made in steel bombs, indicated that decomposition to sodium sulphide, sulphate and thiosulphate begins to take place at some temperature between 530 and 560 F.

ASSOCIATION NOTES.

ANNUAL ELECTION.

The following have been elected officers of the Society for the calendar year 1938:

President:
Rear Admiral H. G. Bowen, U. S. N.

Secretary-Treasurer:
Commander R. W. Paine, U. S. N.

Council:
Captain Albert Norris, U. S. N.
Captain J. M. Irish, U. S. N.
Captain H. T. Smith, U. S. N.
Captain H. S. Howard (CC), U. S. N.
Captain H. F. Johnson, U. S. C. G.
Mr. B. W. Blair.
Mr. H. B. Gregory.

ANNUAL BANQUET.

The Annual Banquet of the Society will be held on Thursday, 7 April, 1938, at the Willard Hotel, Washington, D. C. Details are being arranged and will be promulgated in the very near future.

MEMBERSHIP.

The following have joined the Society since the publication of the November, 1937, JOURNAL:

NAVAL.

Bay, Thomas J., Lieut. Commander, U. S. Navy.
Brady, Parke H., Lieutenant, U. S. Navy.
Byrne, A. C., 833 East 67th St., Seattle, Wash.

Cattermole, H. E., Lieutenant, U. S. N. R., Marine Dept., Union Oil Co. of California, 1103 Union Oil Building, Los Angeles, Calif.

Farquharson, R. B., Lieutenant, U. S. N. R., Worthington Pump & Machinery Corporation, Homer Building, Washington, D. C.

Gigy, M. J., Lieutenant, U. S. N. R., Worthington Pump & Machinery Corporation, Harrison, N. J.

Hayes, John D., Lieutenant, U. S. Navy.

Lienhard, George Harold, Ensign, U. S. N. R., 230 West Mowry St., Chester, Pa.

Lovejoy, J. D., 332 North Maple Avenue, East Orange, N. J.

Simon, Sylvester W., Lieutenant, U. S. N. R., 346 New York Avenue, Brooklyn, N. Y.

Stott, George W., Lieutenant, U. S. Navy.

CIVIL.

Bruckner, Walter H., 214 Transportation Bldg., College of Engineering, University of Illinois, Urbana, Ill.

Hoelzle, Frank C., Apt. 1116, Annapolis Hotel, Washington, D. C.

Jerguson, Philip A., Winter Hill, Somerville, Mass.

Lindenau, Paul, Klaipeda-Memel, Lithuania.

Messersmith, C. E., 326 Glenwood Drive, Ambridge, Pa.

Smaltz, John C., 15 Park Row, New York, N. Y.

Swift, George E., District Manager, Machinery Mfg. Co., 112 South 16th St., Philadelphia, Pa.

ASSOCIATE.

Giavvedoni, Carlos A., Engineer, Argentine Navy, Cordoba 1896, Buenos Aires, Argentine Republic.

Houser, A. C., 901 Hill Bldg., Washington, D. C.

Wilhoff, H. M., American Steel & Wire Works, Electrical Cable Works, Worcester, Mass.